PROJECT SHARK

Hughes Tool Company

Aircraft Division

Culver City, California

Final Report Phase C

Contract Nonr-821(00)

Report No. 09-177-D

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Department of the Navy

Office of Naval Research

SECRET

PROJECT SHARK • PHASE C

Contract Nonr 821 (00)·Annex B, Phase C

1 MARCH 1954

Thermodynamics of Blowing Water Ballast

This document has been reviewed in accordance with OPNAVINST 5510 17, paragraph 5. The security classification assigned is correct.

Date: 9/17/57 By direction of Chief of Naval Research (Code 463)

HUGHES TOOL COMPANY

AIRCRAFT DIVISION · CULVER CITY, CALIFORNIA

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Final Report, Annex B, Phase C, under Contract Nonr 821(00) sponsored by Department of the Navy, Office of Naval Research.

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SUMMARY

Techniques for generating partial standby buoyancy and full attack buoyancy in the Target-Seeking Mine were proposed in the Phase A study of Contract Nonr 821(00). The object of the present study (Phase C) was to determine, experimentally, the feasibility of a water-reactant gas generator for generating and maintaining initial standby buoyancy, and a solid propellant gas generator for achieving full attack buoyancy by ballast ejection. The lack of a firm technical basis for an analytical treatment made necessary an empirical approach to the evaluation of the processes involved and the determination of the range of the major design parameters.

For the tests pertaining to ballast ejection by means of a solid propellant, conventional techniques were used to design rocket-motor type gas generators using JPL-128 propellant to deliver gas at constant rate with external pressures varying up to 1500 psi. These generators were fitted

into a test cell that substantially duplicated the ballast chamber and water environment of the proposed mine. The test cell was installed in a large pressure tank, and firings were made at ambient pressures up to 1000 psi. Information was obtained on the rate and degree of ballast ejection, on differential pressures developed on the cell during ballast ejection, and on subsequent heat flow through the insulated cell wall. Qualitatively, the results indicate that this type of gas generator can be incorporated into the mine without serious design problems. Quantitatively, approximately 20 pounds of JPL-128 propellant will be required to eject ballast from the mine proposed in Phase A, at the maximum design depth of 500 fathoms.

For the tests pertaining to the generation of an initial standby buoyancy on descent, a gas generator consisting of a shallow wire basket containing granulated calcium hydride was fitted into the test cell in the pressure tank. The tank pressure was increased at a rate corresponding to an expected rate of descent of 15 feet per second. The ballast level was maintained within sufficiently close limits during the pressure increase to indicate that reaction rate at high pressure will not be a problem. It is not expected that a generator of this simple design will meet all the requirements of a long standby period, but the basic design is sound.

I. INTRODUCTION

Annex A, Phase A of Contract Nonr 821(00), investigated the feasibility of a deep-water target-seeking mine propelled by buoyancy. From the examination of a number of hypothetical mining missions, it was concluded that the mine should have a design depth range of 100 to 500 fathoms in order to realize the strategic utility expected of a deep-water mine. Annex B, Phase C, covers the investigation of two of the most promising methods for achieving standby and attack buoyancy.

The use of buoyancy was envisioned not only as a novel and expedient scheme for developing propulsive force, but also as one that would result in a relatively low self-noise level. The following criteria were considered of prime importance in the selection of a suitable method for the realization of the buoyancy.

1. The system must allow sufficient net buoyancy to develop the required mine speed
2. The resultant overall weight of the mine and accessories must not be prohibitive for laying from aircraft
3. The full buoyancy must be available soon after launching, and because noise would almost certainly be involved, the process of generating buoyancy should take as little time as possible without compromising other design requirements
4. The system must be adaptable to the range of depths involved, and must be reliable at these depths for a standby period up to six months
5. There must not be undue problems or safety hazards involved in storage, handling, servicing, and laying (particularly by aircraft)
6. Chemicals used in the system must be readily available in quantity and at reasonable cost

Section 4 of the Phase A study described four possible ways of achieving the required mine buoyancy, and concluded that the use of a solid propellant gas generator to eject ballast was the most immediately practicable approach within the above criteria. One of the better known solid propellants (AN525) was chosen for an analytical investigation to determine the approximate generator and fuel weights required for the proposed range of depths. However, the process of burning a solid propellant at high ambient pressures in a ballast chamber containing water, and the subsequent cooling of the hot gases

under these conditions, involves a highly complex thermodynamic problem not susceptible to theoretical analysis. This established the need for an experimental determination of the propellant weights required for ballast ejection at various depths.

The second problem is one of generating and maintaining sufficient buoyancy to keep the mine floating erect above its anchor. This buoyancy is desired also during the mine's descent, in order to limit the sinking speed and to prevent its striking the bottom. A consideration of the design problems involved indicated that the most promising method of achieving this result would be to generate a gas with a water-reactive chemical. This implies an automatically controlled rate of reaction that would provide a constant displacement with increasing ambient pressure. Information relative to the rate and character of the reaction as influenced by pressure, granulation, and environment was not available, so an experimental approach was indicated here as well.

The present report summarizes the experimental work done with a solid propellant gas generator for ballast ejection, and a water-reactant gas generator for maintaining partial buoyancy.

II.

OUTLINE OF STUDY

PURPOSE

The purpose of this study was to evaluate, by experimental methods, the major design parameters involved in the ejection of ballast by means of a solid propellant gas generator and in the maintenance of partial buoyancy by means of a water-reactant gas generator.

SCOPE

In the initial considerations given to the possibility of experimental determination of reactant weights required for the generation of buoyancy, it became apparent that the high pressures involved made it advantageous to conduct such tests on a reduced scale. However, an assessment of the several possible factors entering into the process indicated that even with a precise knowledge of individual factors it would still be difficult to extrapolate

the results to full scale. On the other hand, in full-scale measurements, the basic information on propellant weight could be determined with sufficient accuracy for design purposes without a complete evaluation of all the aspects of the process, provided the tests were conducted under contemplated design conditions. An attempt was therefore made to duplicate as closely as possible the anticipated design of the 28-inch mine proposed in the Phase A study, and to test one solid propellant and one water-reactive chemical that promised to meet the requirements of this application.

The conclusions of this study therefore apply quantitatively to this particular set of design conditions and reactants and may be extrapolated with reasonable confidence to moderate variations of this situation. Qualitatively, the results should be useful in designs that are radically different.

APPROACH

In the Phase A study, the shape and size of the mine were selected from a general approach, and confirmed by an estimate of drag, maximum permissible weight, and the resultant terminal velocity. This defined the ballast displacement required for propulsion. A further study of the problems pertaining to the descent and anchorage of the mine defined the displacement required for partial buoyancy. Probable reactants were selected for generating the gas to effect these displacements, and the attendant design problems were evaluated and incorporated into a proposed configuration.

Since it appeared advisable to conduct the tests at full scale, it was decided to design a ballast chamber that would closely duplicate the portion of the mine reserved for partial buoyancy and ballast displacements, and to simulate by suitable means the environmental conditions of the mine.

The first and most important facility requirement was a pressure vessel of sufficient size to accept the test cell, of sufficient volume to keep pressure rise during the tests to a minimum, and of sufficient pressure rating to permit testing up to the maximum expected ambient pressure. In addition to the possibilities of fabricating such a vessel, investigations were made of existing facilities at NOTS Foothill Annex, Naval Ordnance Laboratory, and Navy Electronics Laboratory. The vertical pressure tank at Navy Electronics Laboratory (Battery Whirtler, Code 570) came nearest to meeting the basic requisites. It also had the desired arrangement and necessary auxiliaries, and fortunately was available for the tests.

The test cells were fitted with gas generators designed to perform as required in the final application. Structurally, the design was liberal and provided special features and adequate margins of safety against test hazards.

The primary measurement was to be rate of ballast displacement at various ambient pressures, and was obtained by recording ballast level versus time. Because of the limited volume of the pressure tank, an increase in ambient pressure was expected during ballast ejection. Substantial pressure differentials across the ballast chamber wall were also expected during this period, and provisions were made for recording both these pressures. It was also felt that some useful design information concerning the process might be obtained by local measurements of temperature and heat flow, and thermocouples were installed for that purpose. In addition, elements were incorporated into the design of the test equipment, instrumentation, and control to provide the maximum protection against known and suspected hazards.

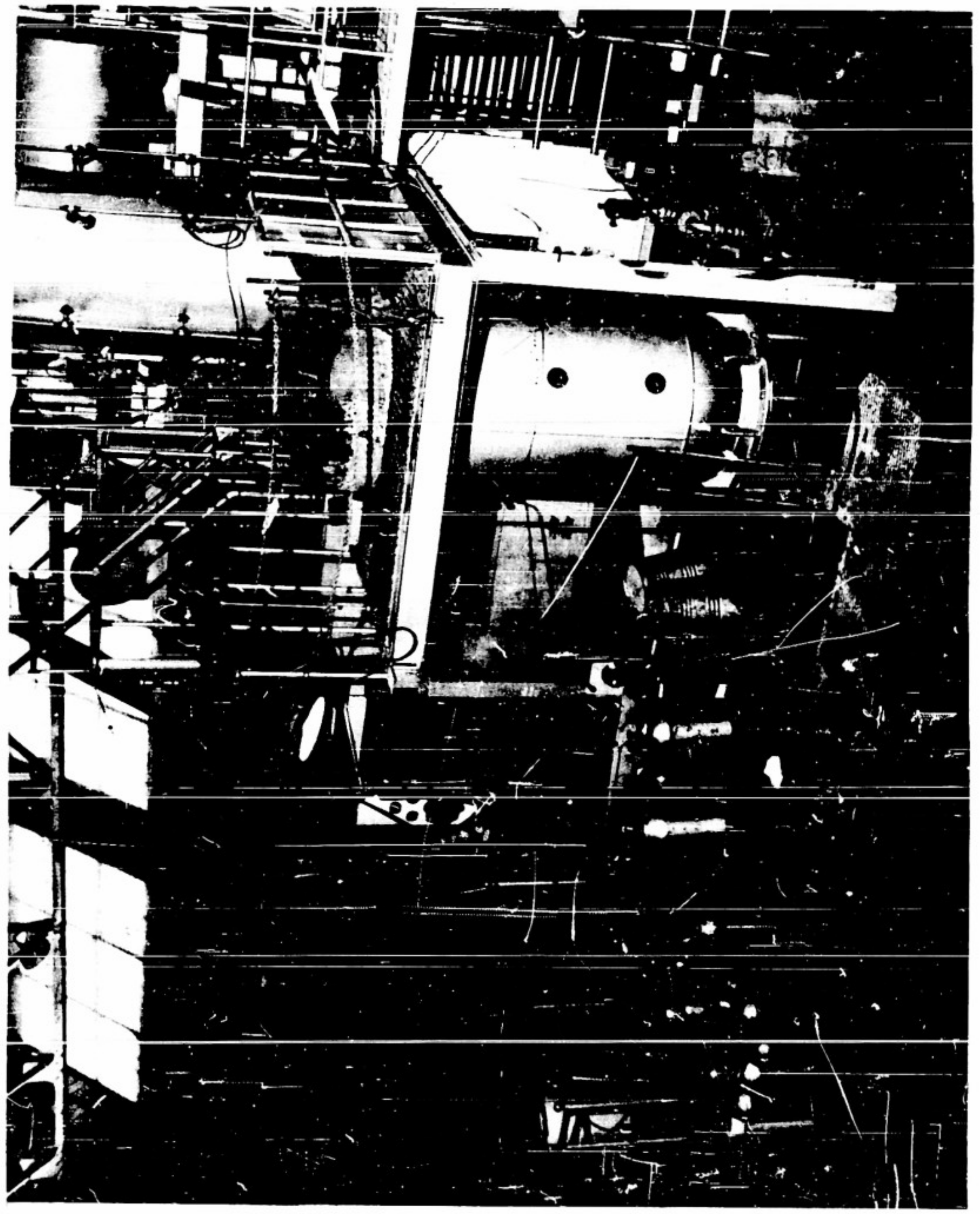


Figure 1. Test Installation at Navy Electronics Laboratory

III.

PROCEDURES AND RESULTS

Ballast Ejection Tests

TEST FACILITIES AVAILABLE

The primary piece of equipment at Battery Whistler, Navy Electronics Laboratory, is the large pressure tank shown in Figure 1. This tank is a vertically mounted cylinder with hemispherical ends, the top hemisphere being a removable cover. It has an inside diameter of 56 inches, an inside height of 143 inches, and a volume of 170 cubic feet. The maximum allowable peak operating pressure is 1500 psi when filled with water and 1000 psi when filled with gas. A total of nine portholes are arranged at three levels and at 120 degrees around the circumference, and are closed with covers to which plumbing fittings can be attached or through which cables can be passed and sealed. The tank can be pressurized from a 3000-psi air storage tank, can be filled with water at the bottom, and can be vented at either the bottom or the top. Dial pressure gages in several ranges are attached to the tank.

The availability of safety shelters, shop facilities, and darkroom facilities contributed greatly to the tests.

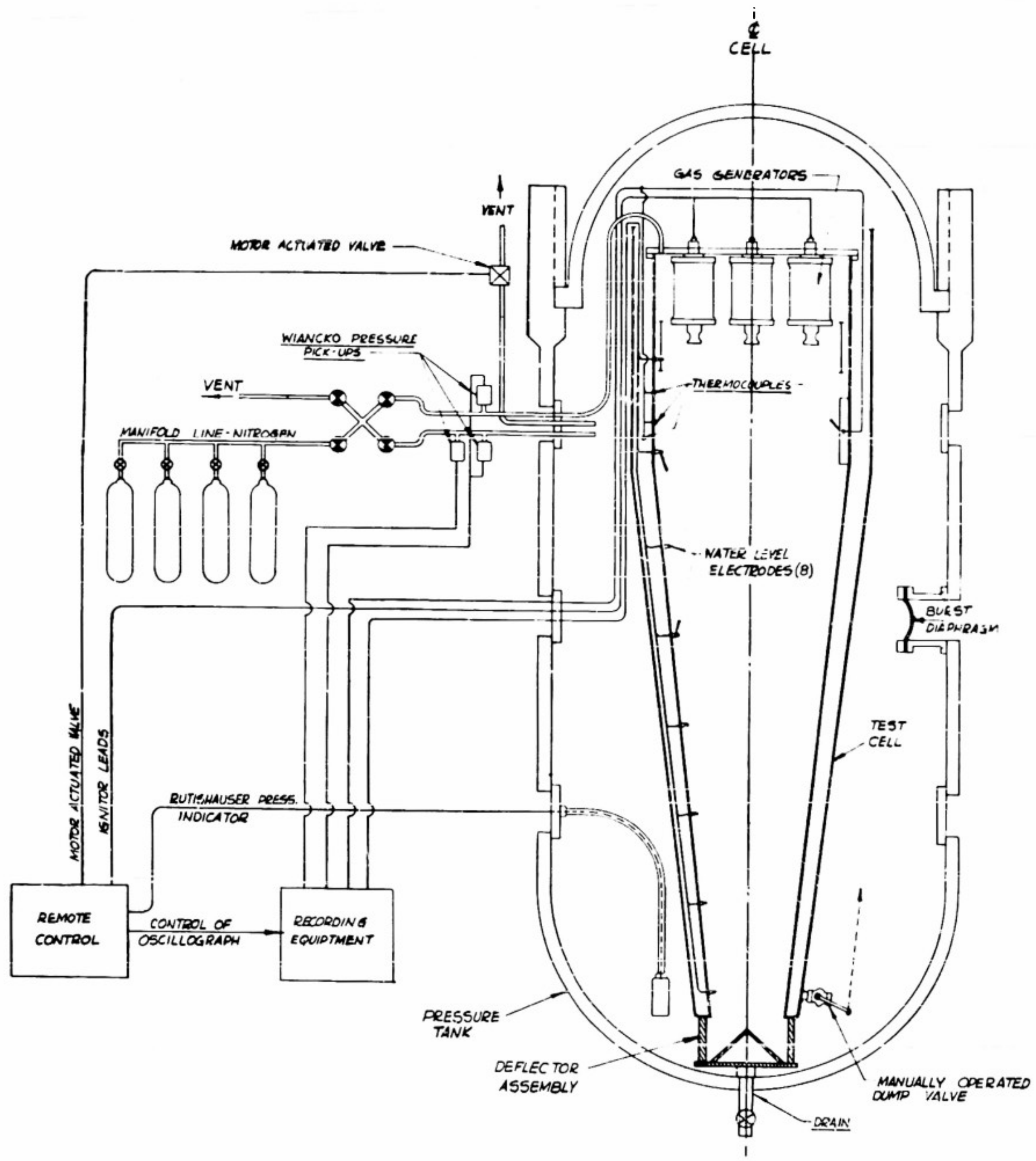


Figure 2. Schematic Diagram of Pressure Tank, Test Cell, and Instrumentation for Ballast Ejection Tests

BASIC TEST AND INSTRUMENTATION PLAN

Test Cell

The test cell is composed of a ballast chamber from which ballast is to be ejected, a jacket for holding cooling water around the ballast chamber, a deflector assembly that reacts jet thrust and acts as a support, and tension rods that hold the test cell assembly positioned within the pressure tank. A schematic diagram of the entire test setup is shown in Figure 2.

The ballast chamber is an approximation to the aft 23.9 cubic feet of the 36.8-cubic-foot mine body considered in Reference 1, with the curved

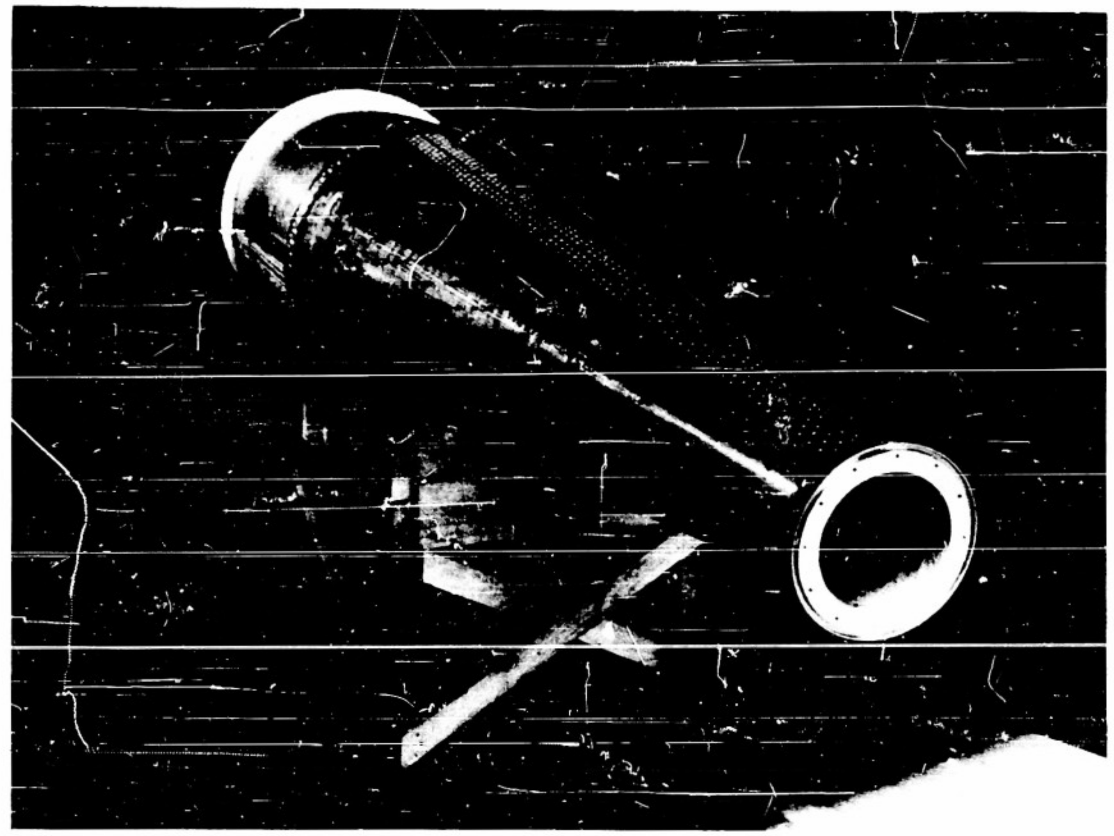


Figure 3. Original Ballast Chamber

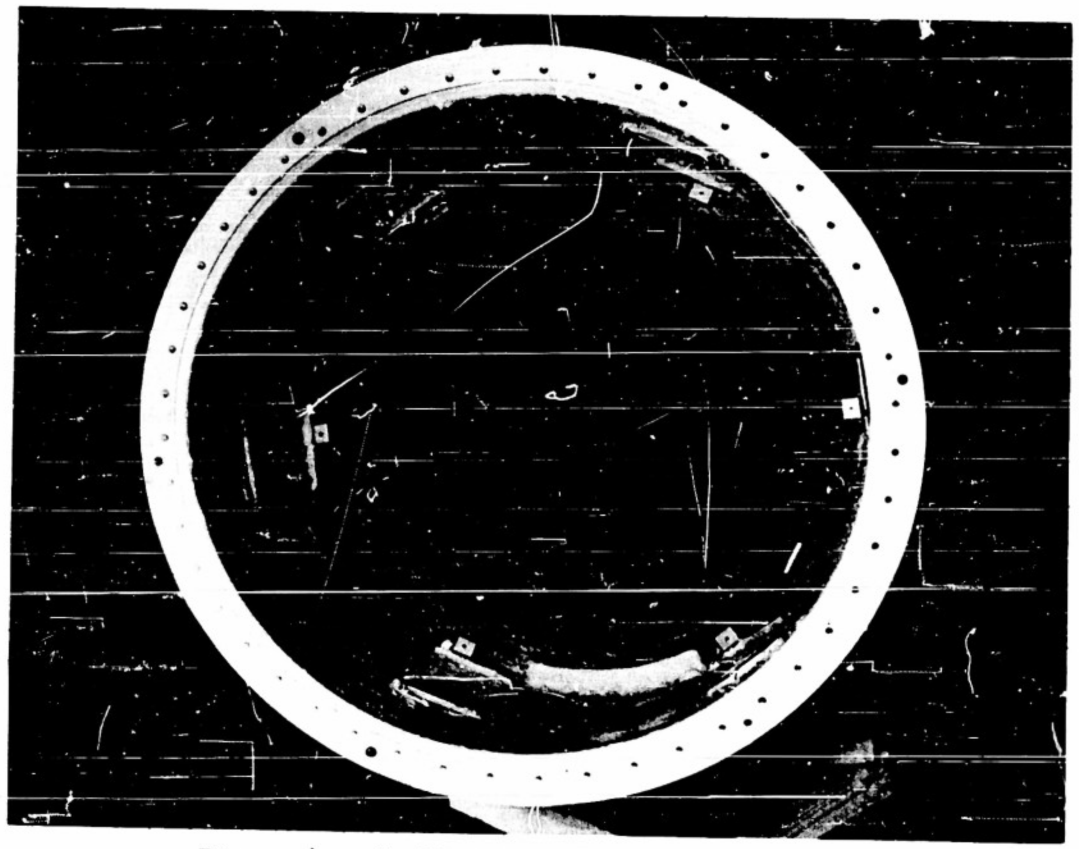


Figure 4. Inside View of Ballast Chamber

contour of the Lyon's body approximated by a cylindrical and a conical section. The cylinder is 31 inches long and 28 inches in diameter, and the cone is 82 inches long and 8 inches in diameter at the small end. The large end is fitted with an end ring to which a bulkhead and three tie-down rods are attached. The small end is attached to the water jacket and to the deflector assembly.

The inside of the ballast chamber was coated with 0.1 inch of Stabond HT-12 for thermal insulation. This material is a Buna rubber dissolved in a

suitable solvent and filled with glass fibers. A finish coat of Buna rubber (Stabond C-111) was applied over the HT-12.

Various views of the ballast chamber, water jacket, and the deflector are shown in Figures 3 through 6.

Pressurization and Venting System

For the purpose of rapidly pressurizing the system by adding nitrogen to either the tank or to the test cell a manifold was constructed to which four nitrogen cylinders could be connected simultaneously through flexible

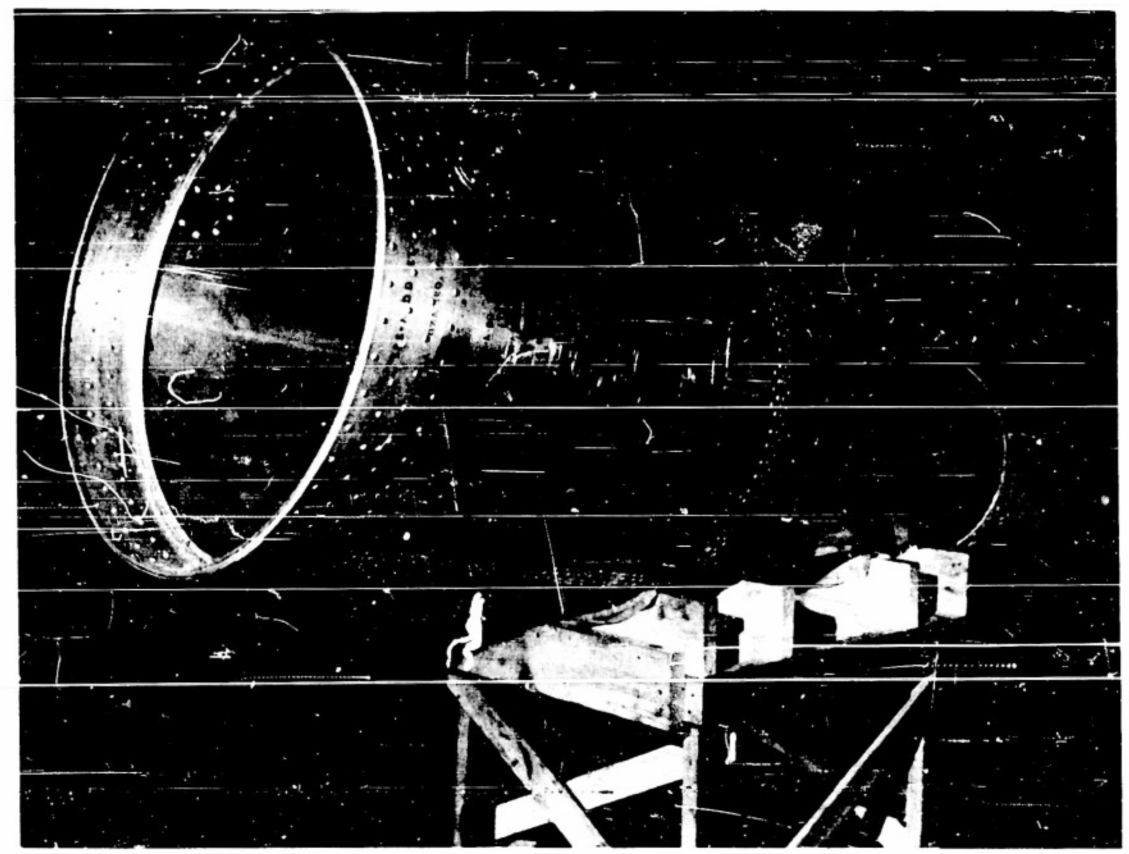


Figure 5. Water Jacket

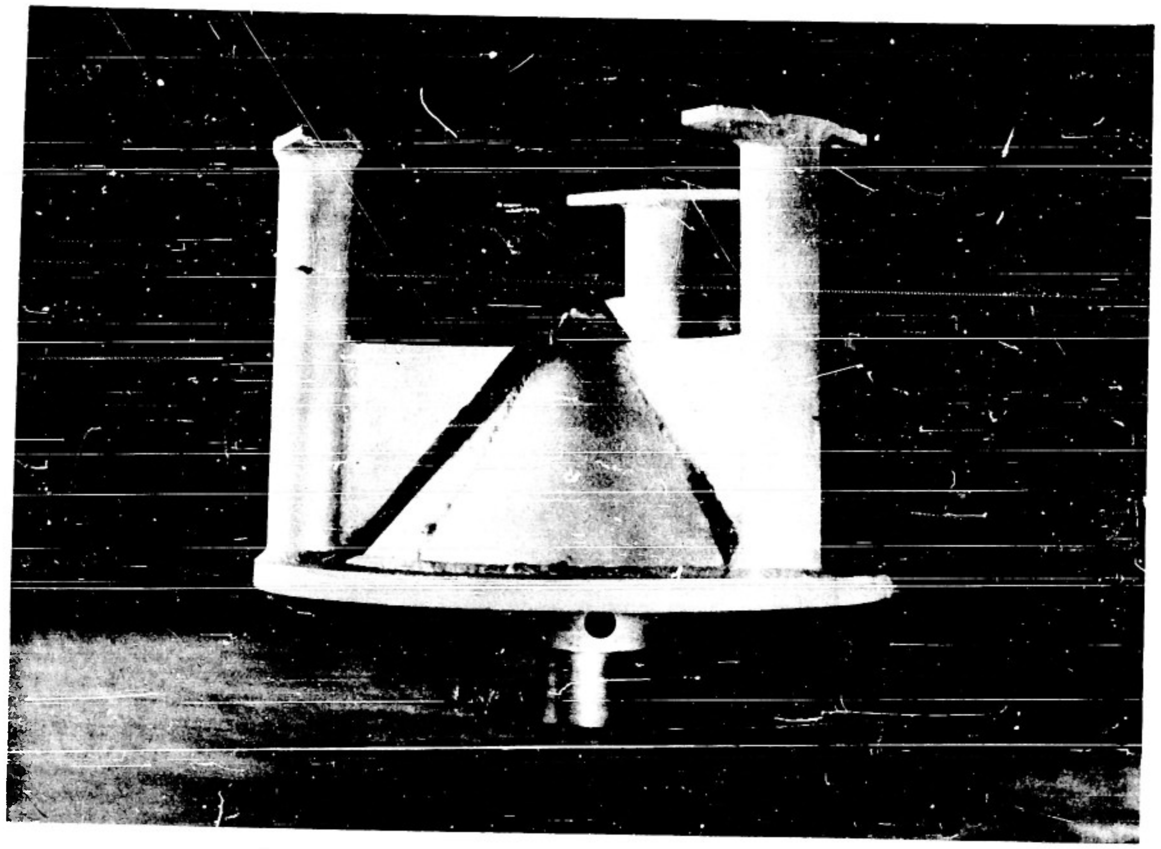


Figure 6. Jet Deflector

hoses. From the manifold a 3/8-inch tube led to a system of four valves, which allowed the manifold to be connected either to the tank or to the bulkhead of the test cell through a flexible hose within the tank. This system of valves (Figure 7) also allowed either the tank or the cell to be vented. To keep constant check on the pressure, dial gages were connected to the tank and located at both the manifold and remote control positions.

In order to simulate the pressure drop corresponding to an ascending mine, a 3000-psi, 3/4-inch steam valve was equipped with a motor and connected

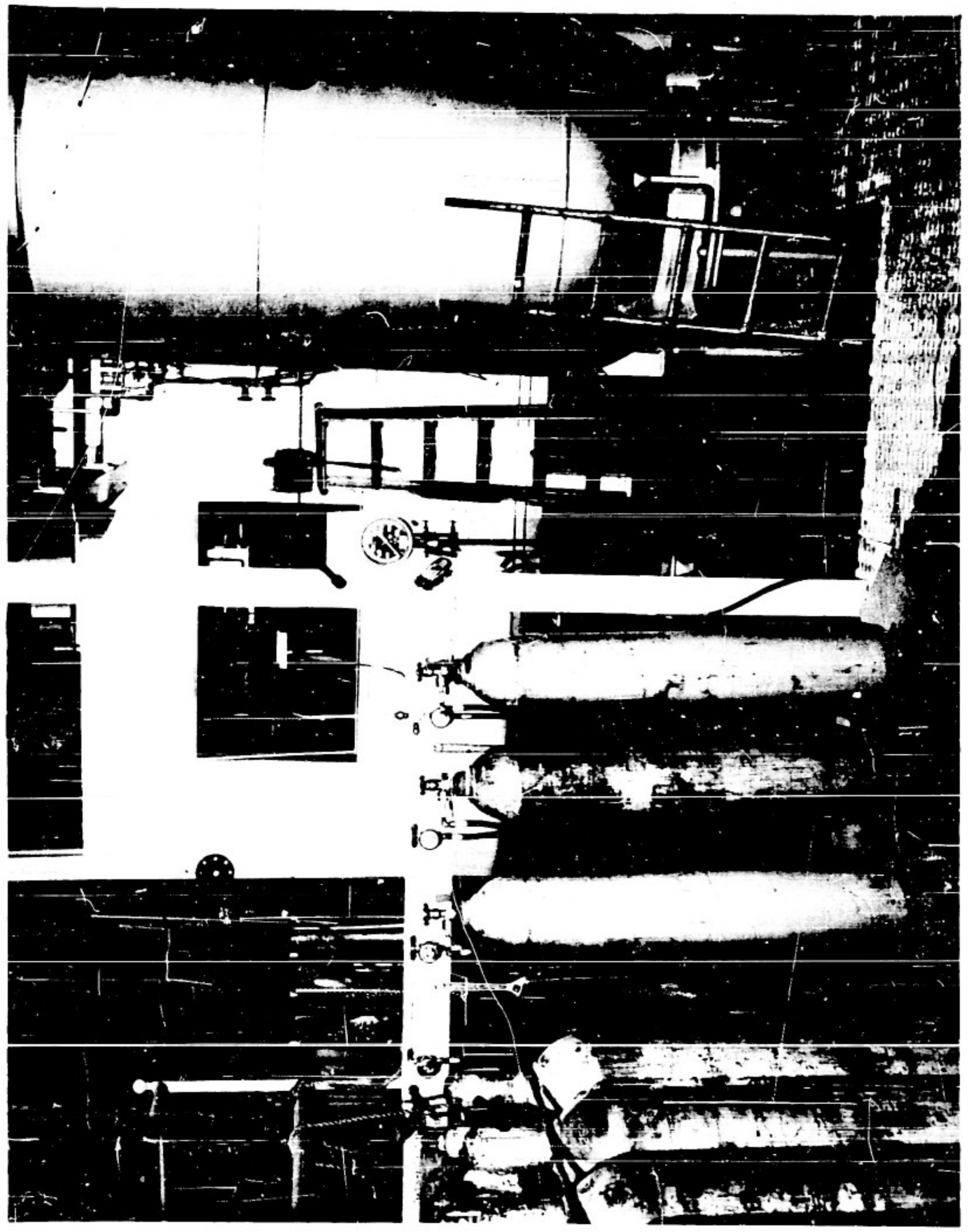


Figure 7. View of Pressurization System

to the tank, and was vented to the outside of the building through $1\frac{1}{2}$-inch pipe. The valve was operated from the remote control position.

Gas Generators

There were a number of requirements that the solid propellant rocket motors, acting as gas generators, had to meet. The burning time had to be about $1\frac{1}{4}$ seconds as a compromise between completing the ballast ejection process as soon as possible and keeping the pressure differential across the skin of the mine within reasonable bounds, and this time had to be independent of ambient pressure up to 1450 psi. It was also required that the total mass of gas be adjusted to correspond to the depth at which ballast ejection was to occur. In order that the process be efficient, the combustion gas had to have a low molecular weight and a low solubility in water.

The solid propellant considered in the Phase A study was AN-525. The propellant chosen for these tests, JPL-128, has very similar characteristics.

Instrumentation

As stated earlier, instrumentation was needed to obtain ballast level, tank pressure, ballast chamber pressure differential, various temperatures, and heat flow through the thermal insulating material. It was desired to record all this data simultaneously on an oscillograph operated from a remote location. The general plan of instrumentation is shown in block diagram form in Figure 8.

Several methods for continuously indicating the ballast level within the ballast chamber were considered, but they were rejected because of the

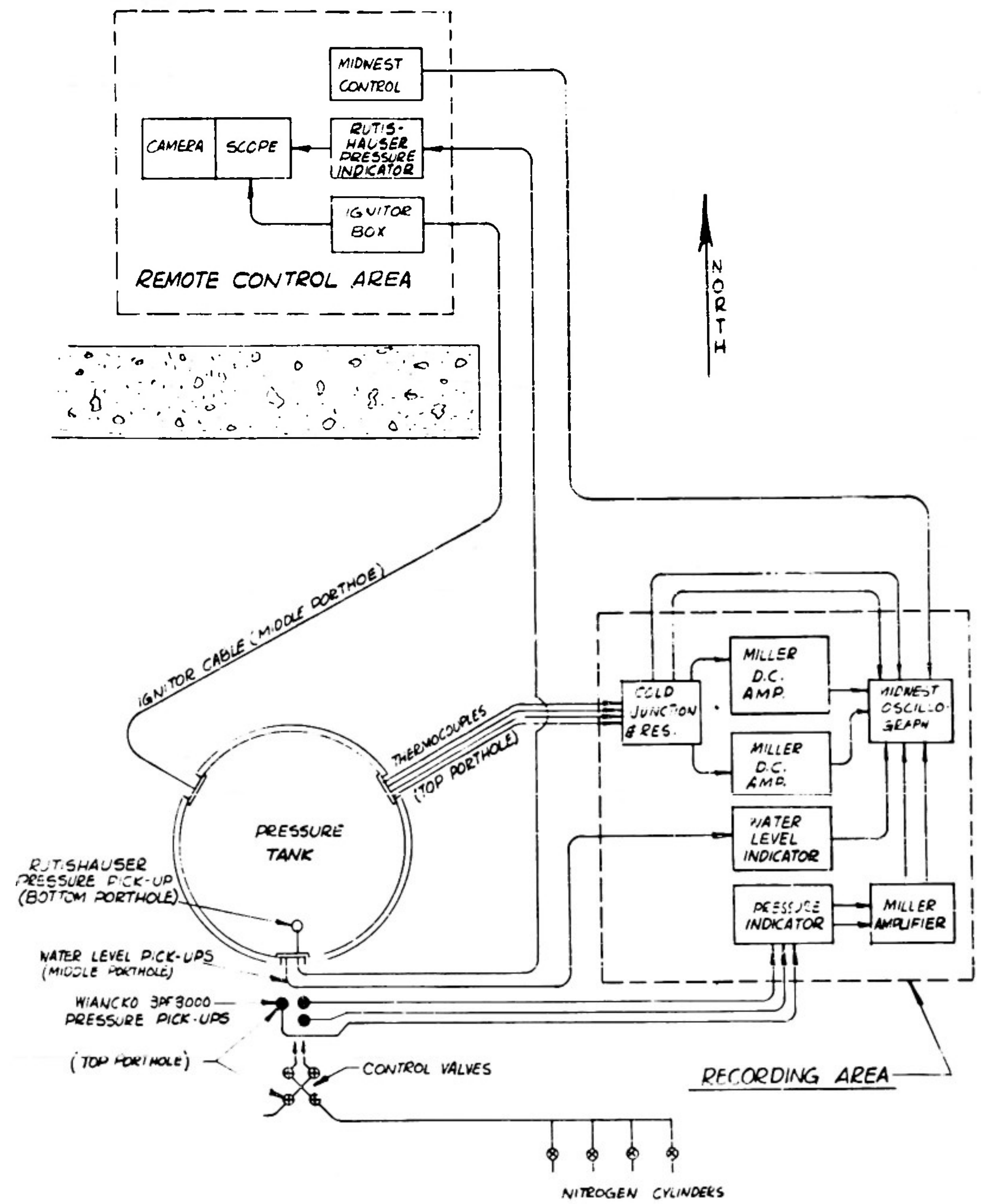


Figure 8. Block Diagram of Instrumentation

adverse conditions under which the system had to operate. Preliminary tests showed that the alternating current resistance across the terminals of an automotive spark plug, used as an electrode and feed-through insulator, could give a good indication of submergence in dilute salt solution even though the spark plug was wet with concentrated hydrochloric acid during the nonsubmerged condition. A system was then designed that could indicate how many of a vertical series of spark plugs were covered by the ballast, and hence, give a stepwise indication of the ballast level.

For measuring tank pressure and ballast chamber pressure differential, standard pressure pickups were used, the pressure differential requiring two pickups connected so that only their difference was recorded.

It was decided that the measurement of three temperatures might yield useful secondary data. These were the temperature of the ballast chamber skin, the water in the water jacket, and the surface of the thermal insulating material within the ballast chamber. Iron-constantan thermocouples were used in each case.

As a means for estimating the relative amounts of heat lost through the thermal insulating material and directly to the ballast, it was decided to obtain a local measurement of heat flow through the insulation. Of the various methods considered for measuring heat flow, the temperature rise in a calorimeter block was considered most satisfactory. Since no way could be found for thermally insulating a section of the ballast chamber skin from the remainder without encountering difficult structural problems, a slab of aluminum was placed internal to the skin and thermally insulated from it.

This slab was covered by the same HT-12 insulating material as the inside of the chamber. The temperature of the block at six-tenths of the distance from the outer face was measured with an iron-constantan thermocouple.

The rocket firing circuit was designed to check individually up to seven rocket motor ignitors for deviations from their normal resistance and to fire them all simultaneously. Provision was made for keeping the ignitors shorted at all times except just prior to firing, as an additional safety precaution.

SAFETY PRECAUTIONS

The most important problems from a safety standpoint were those of preventing unintentional ignition of the gas generators or their ignitors and in taking precautions to see that unduly high pressures did not jeopardize the tank. In order to anticipate conditions that might inadvertently have produced peak pressures beyond the 1000 psi maximum allowable, the assumption was made that the test cell would rupture, permitting free mixture of the combustion and pressurizing gases. Calculations, summarized in Figure 9, indicated that secondary burning of the rocket gases and pressurizing air could substantially increase the final pressure. It was therefore decided to use bottled nitrogen to purge the air and to develop the initial ambient pressure.

A Rutishauser pressure gage, with a flat frequency response to over 30,000 cycles per second was installed to indicate transient pressures of such short duration that they would not be detectable by the recording instrumen= tation. The output of the Rutishauser system was displayed on an oscilloscope

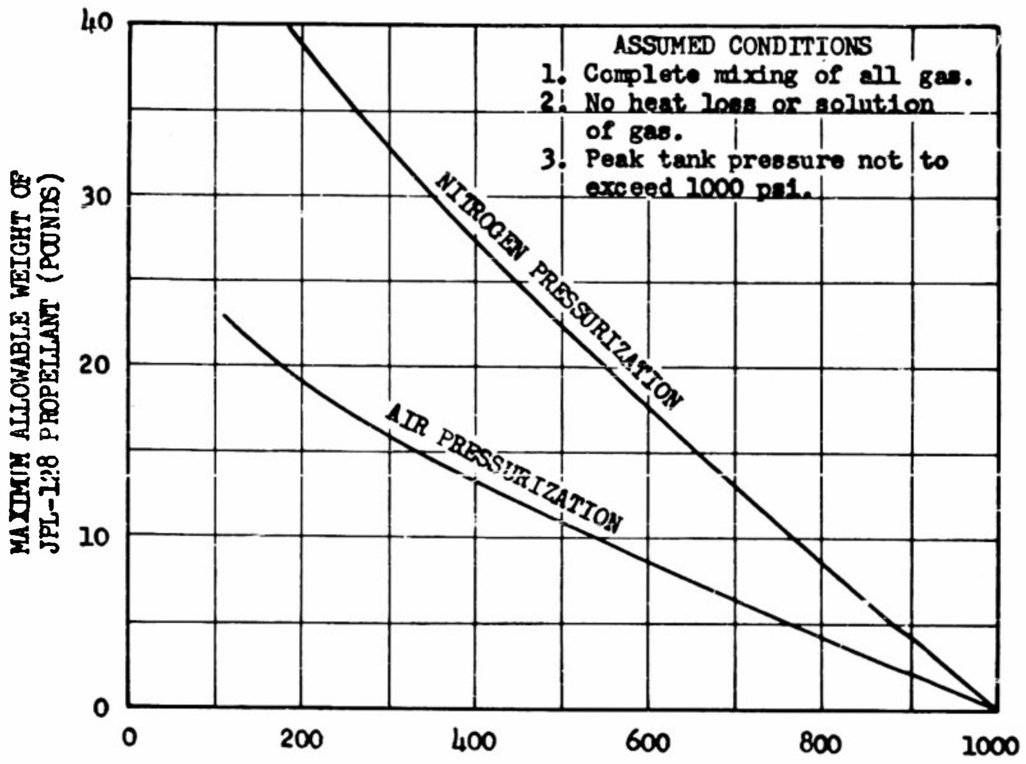


Figure 9. Computed Values of Maximum Allowable Propellant Weight

and photographed with a Polaroid Land camera. These photographs are shown in Figure 10. The photograph taken during Test No. 1 indicates a series of positive pressure peaks while that taken during Test No. 2 shows a series of negative pressure surges. Since the high average pressure indicated in Test No. 1 does not show up in other pressure instrumentation and the negative pressure surges obtained in Test No. 2 could be simulated by light tapping on the pickup mount, it was decided that the system was not operating satisfactorily and its use was discontinued.

As an additional precaution against high pressures the Navy Electronics Laboratory equipped the tank with a burst diaphragm four inches in diameter and designed to rupture at 1450 psi. Peak pressure indicators of the type that are used to measure pressures in ice flows were also placed in the tank. These gave results comparable to those obtained with the other instrumentation.

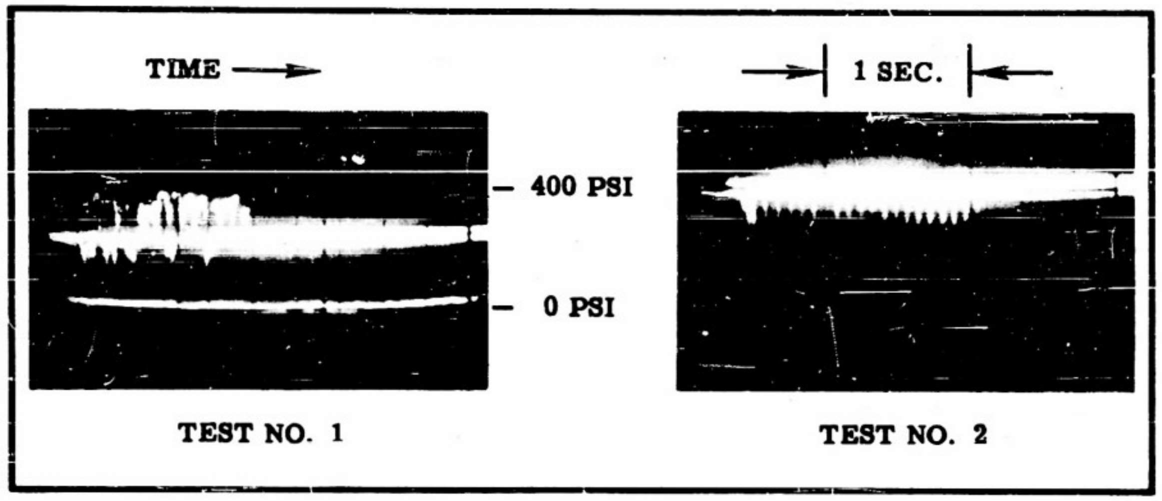


Figure 10. Transient Output from Rutishauser Pressure Indicating System

As a final precaution against the possibility of tank rupture, all personnel retired to safety shelters that provided a minimum of five feet of concrete between the tank and the remote control position.

PRE-TEST ANALYSIS

Gas and Liquid Volumes

As the volumes of the tank, ballast, gas in the tank, etc., will frequently be used in the remainder of the report, they are given in Table 1.

TABLE 1
VOLUME DISTRIBUTION WITH BALLAST AT INITIAL LEVEL

Ballast	29.3 cubic feet
Jacket Water	16.5
Equipment	2.0
Initial Gas in Cell (Including Rocket Motors)	5.8
Initial Gas in Tank	116.4
Total Tank Volume	170.0 cubic feet

Pressure Differential and Thrust

As indicated in Reference 1, it had originally been planned to have the gas for initial buoyancy separated from the chamber from which the water was to be expelled. After a basic layout of the test cell had been made, a theoretical investigation was begun to determine what the transient pressure would be if the rocket motors were discharged into the test cell with no initial gas space. Assuming that the flow of gas would be a step function, it was apparent that the pressure rise would be very large and that an initial space was necessary as a pressure buffer.

Since the pressure tank limited the length of the test cell, it was decided to proceed with a total volume of 24 cubic feet and allow five cubic feet of this volume for initial gas space. This resulted in a slightly reduced volume of water to be expelled, but the difference was not considered large enough to invalidate the results.

Assuming that a total volume of gas large enough to expel the water in $1\frac{1}{4}$ seconds is delivered in the form of a step function, that any compression is isothermal, and that the pressure rise can be divided between the hydraulic

nozzle drop and pressure required for the transient acceleration of the ballast, a differential equation in terms of the pressure differential was written. Graphical solutions of this equation obtained by several methods for the initial stages of ballast blowing indicated a peak pressure of approximately 95 psi at about 0.045 second.

The thrust resulting from the expulsion of the ballast, computed from the two components of pressure differential, has a peak of 8500 pounds, of which 4000 pounds results from the nozzle drop.

Propellant Required

As a limiting case in expelling the water ballast, it may be well to examine the theoretical situation where no heat is lost and no gases are lost to solution.

It will be assumed that the initial gas space is occupied by nitrogen and that the combustion gas arrives in the buoyancy chamber by a throttling process and is therefore at flame temperature before mixing occurs.

Let V_n = initial volume occupied by nitrogen
V_t = total volume
N_n = initial number of mols of nitrogen
N_g = mols of combustion gas
T_n = initial nitrogen temperature
T_g = combustion gas temperature
T_f = final temperature of mixture
C_{pn} = mean heat capacity of nitrogen at constant pressure between T_n and T_f
C_{pg} = mean heat capacity of combustion gas at constant pressure between T_f and T_g

The heat balance relationship can be written

$$N_g C_{pg}(T_g - T_f) = N_n C_{pn}(T_f - T_n)$$

Also,

$$N_t \equiv N_n + N_g$$

And by the perfect gas equation (assuming no ambient pressure rise),

$$pV_t = N_t R T_f$$

$$pV_n = N_n R T_n$$

These four relationships can be combined to give

$$\frac{\frac{V_t}{V_n}}{\frac{N_g}{N_n} + 1} = \frac{\frac{N_g}{N_n} + \frac{C_{pn}}{C_{pg}}\frac{T_n}{T_g}}{\frac{N_g}{N_n}\frac{T_n}{T_g}\frac{C_{pn}}{C_{pg}}\frac{T_n}{T_g}}$$

Using the properties of JPL-128 propellant shown in Table 2, which were obtained from Grand Central Aircraft Company, Rocket Division, Pacoima, California, the following values are assigned.

V_t = 23.64 cubic feet

V_n = 5.84 cubic feet

$C_{pg} = 10.2 \frac{\text{Btu}}{(\text{lbm-mol})(^\circ\text{F})}$ (Computed from γ)

$C_{pn} = 7.3 \frac{\text{Btu}}{(\text{lbm-mol})(^\circ\text{F})}$

T_g = 4789° R (4329° F)

T_n = 530° R (70° F)

TABLE 2
PROPERTIES OF JPL-128 PROPELLANT

1. Composition of combustion gas.

Constituent	Molecular Percentage
HCl	15.2
N_2	8.0
H_2	15.0
H_2O	29.5
CO	19.0
CO_2	5.5
SO_2	4.5
S_2	0.3
H_2S	1.3
OH	0.1
H	0.2
Fe_2O_3	0.1
S	0.8

2. γ = ratio of specific heats = 1.243.

3. Flame temperature = 4329° F.

4. Average molecular weight = 25.8.

The above relationship can now be solved for N_g/N_n

$$\frac{N_g}{N_n} = 0.268$$

Using the perfect gas equation and the average molecular weight of the combustion gas gives

$$W_p = 0.00712\ p$$

where W_p = weight of propellant (lbm)

p = ambient pressure (psi)

Substituting back into the heat balance equation results in

$$T_f = 1692^\circ\ R \qquad (1232^\circ\ F)$$

In an actual case both heat and soluble components will be lost by the buoyant gas. The loss of components will require the use of more propellant, which will tend to compensate for the temperature drop due to heat loss. Since no better information is available it will be assumed that the final temperature is the same as in the no-loss case and that all gaseous components are lost except for N_2, H_2, and CO. This amounts to retaining 42.0 mol percentage of the combustion gas and will require a corresponding increase in the propellant weight required.

Then,

$$W_p = \frac{0.00712\ p}{0.42} = 0.0170\ p$$

Both the no-loss case and the predicted results are compared with the test results in Figure 42.

DESIGN OF TEST CELL

From the results of the theoretical investigation it was decided that the ballast chamber should be designed for a limit pressure of 110 psi, the

tension rods designed for a total vertical limit thrust of 10,000 pounds, and the deflector assembly designed for a limit force of 5000 pounds to react that component of thrust resulting from the nozzle drop.

It became apparent that in order to achieve the desired results, high strength, non-weldable aluminum alloy for the skin of the ballast chamber and a top end ring of steel would be desirable. For these reasons riveted construction was chosen.

Both the ballast chamber and the water jacket were made from 0.091 24S-T aluminum sheet. The bulkhead was made of inch-thick 24S-T aluminum and held down to the top steel end ring with forty-eight 5/16-24 bolts. The water jacket was held to the small steel end ring at the bottom of the ballast chamber with twelve 1/4-28 bolts, of which six were used for attaching the deflector assembly. O-ring seals were used between the bulkhead and the top ring, and between the water jacket and the bottom ring. Three special eye bolts were designed for attaching the tension rods to the top ring.

It was concluded in Reference 1 that 0.08 inch of insulating material with a thermal conductivity of $\frac{0.2\ \text{Btu}}{\text{hr ft}^2\ {}^\circ\text{F/in.}}$ should be applied to the inner surface of the ballast chamber. This thermal conductivity is probably a good estimate for Stabond HT-12, and an application of 0.08 inch was attempted. However, the finished coat turned out to be much closer to 0.10 inch on both of the two test cells.

Further details of the test cell design can be seen in Figures 3 through 6.

DESIGN OF GAS GENERATORS

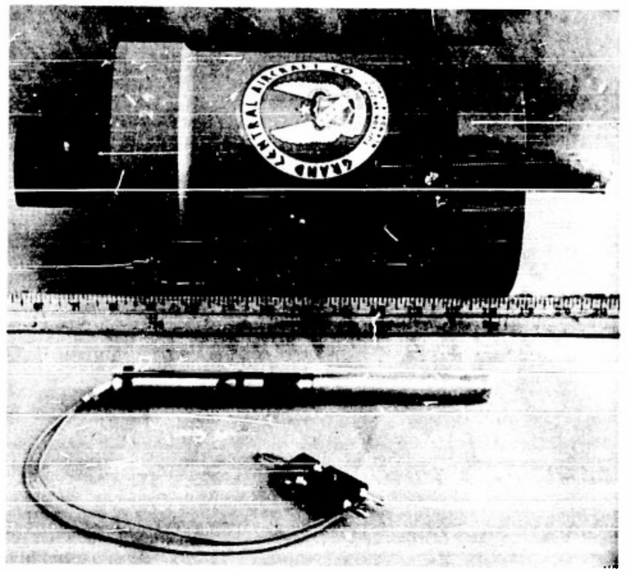


Figure 11. Gas Generator and Ignitor

As stated earlier, it was necessary to have solid propellant gas generators whose burning time was independent of ambient pressure up to 1450 psi, and with the total mass of gas adjustable to correspond to the depth at which ballast ejection was to occur. One way to approximate the desired result would have been to use different generator designs for various depth ranges. It was concluded, however, that it would be better to use a single design with a nozzle that would maintain a high enough burning pressure to establish critical conditions in the nozzle throat for ambient pressures up to 1450 psi, and to adjust the number of motors to give the required mass of gas.

Other design features which were desired were the ability to withstand hydrostatic pressure of 1450 psi prior to firing, safety diaphragms, a removable ignitor, and a gas diffuser to cancel the nozzle jet thrust and to slow the gas flow.

It was decided that the total propellant weight that might be required at the maximum ambient pressure should be divided equally between seven gas

generators since a mounting arrangement of one generator at the center of the bulkhead surrounded by six generators would allow using any number from one to seven in a symmetrical pattern.

The total propellant weight was based on 1450 psi (corresponding to a maximum design depth of 500 fathoms), and a total ballast volume to be ejected of about 24 cubic feet. This led to an estimated propellant weight of 32 pounds, which was increased to 42 pounds (6 in each generator) to allow for a possible underestimation of the weight required. When the ballast volume was reduced to 17.8 cubic feet, the individual motors were somewhat oversize, but were satisfactory for test purposes.

The Grand Central Aircraft Company, Rocket Division, was given an order for the design, development, and construction of 20 rocket motors using JPL-128

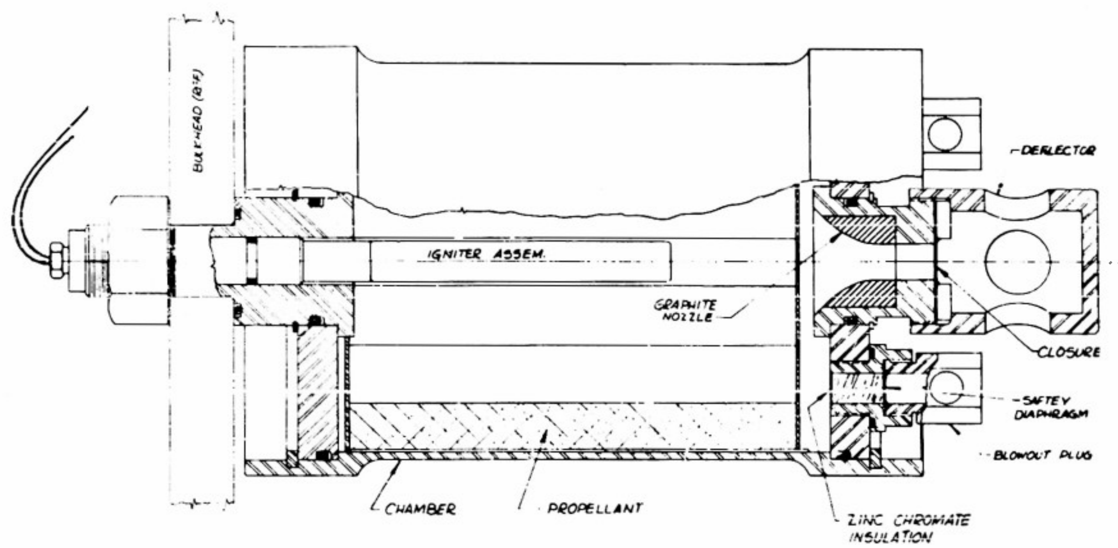


Figure 12. Gas Generator Assembly Drawing

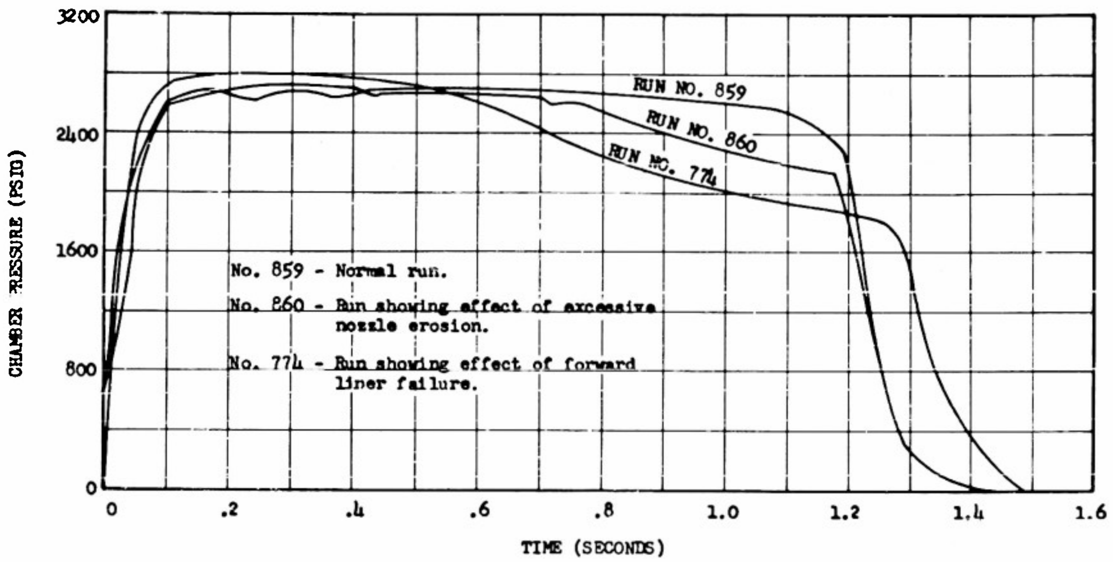


Figure 13. Gas Generator Pressure-Time Curve

propellant. These were to be of conventional and conservative mechanical design, since the schedule did not permit an attempt to achieve minimum weight. During the development, which included approximately 15 static test firings, minor changes in the nozzle, grain shape, and the case liner (burning inhibitor at end of grain) were made.

The final motor design is shown in Figures 11 and 12. Physical and performance data is shown in Table 3. Pressure versus time curves are included in Figure 13 for three test firings made by Grand Central, showing a normal firing and two types of failure that were subsequently corrected.

DESIGN OF INSTRUMENTATION

The Oscillograph

For recording data, a Midwestern Geophysical Laboratory Model 544 18-channel oscillograph was used. Galvanometers were available ranging in

TABLE 3
PHYSICAL AND PERFORMANCE DATA FOR ROCKET MOTOR

Propellant weight, lb	6.0
Total loaded motor weight (including igniter), lb	33.5
Motor weight after firing, lb	27.5
Average chamber pressure at 80° F, psi	2675
Average chamber pressure at 40° F, psi	2530
Effective burning time at 80° F, sec	1.20
Effective burning time at 40° F, sec	1.26
Minimum allowable chamber pressure at 1400 psi ambient pressure at 40° F	2490
Motor hydrotest pressure, psi	4000
Calculated minimum chamber burst pressure, psi	5500
Safety diaphragm burst pressure, psi	3300-3800
Nozzle closure differential burst pressure (pressurized from inside), psi	1200
Nozzle closure burst pressure (pressurized from outside), psi	1700

sensitivity from 0.034 to 36.0 milliamperes per inch and the various instrumentation systems were designed to utilize the existing galvanometers. A control box was built for operating the oscillograph from the remote control position.

The Ballast Level Indicator

The changes in resistance across the spark plugs placed at vertical intervals along the ballast chamber were used to control seven corresponding

thyratron circuits, each thyratron being in a non-conducting condition when its spark plug was submerged (dilute salt solution) and in a conducting condition when the spark plug was out of the ballast. By adding the currents through the thyratrons and passing a portion of the total current through a galvanometer, a galvanometer deflection was obtained in proportion to the total number of spark plugs out of the solution. This in turn was interpreted in terms of the liquid level within the ballast chamber by means of the volumes corresponding to each level as shown in Table 4.

TABLE 4
VOLUMES CORRESPONDING TO BALLAST LEVELS

Level Number	TEST CELL NO. 1 Volume from Level 1 (ft³)	TEST CELL NO. 1 Volume from Bulkhead (ft³)	TEST CELL NO. 2 Volume from Level 1 (ft³)	TEST CELL NO. 2 Volume from Bulkhead (ft³)
1	—	5.34	—	5.34
2	1.68	[illegible]	3.30	[illegible]
3	3.32	[illegible]	[illegible]	[illegible]
4	11.65	[illegible]	[illegible]	[illegible]
5	14.14	[illegible]	[illegible]	[illegible]
6	15.38	21.73	15.72	21.55
7	17.03	22.37	[illegible]	[illegible]
8	17.88	23.53	[illegible]	[illegible]
End	17.90	23.54	[illegible]	[illegible]

Note: Test Cell No. 1 was used for Tests 1 and 2
Test Cell No. 2 was used for Tests 3 and 4

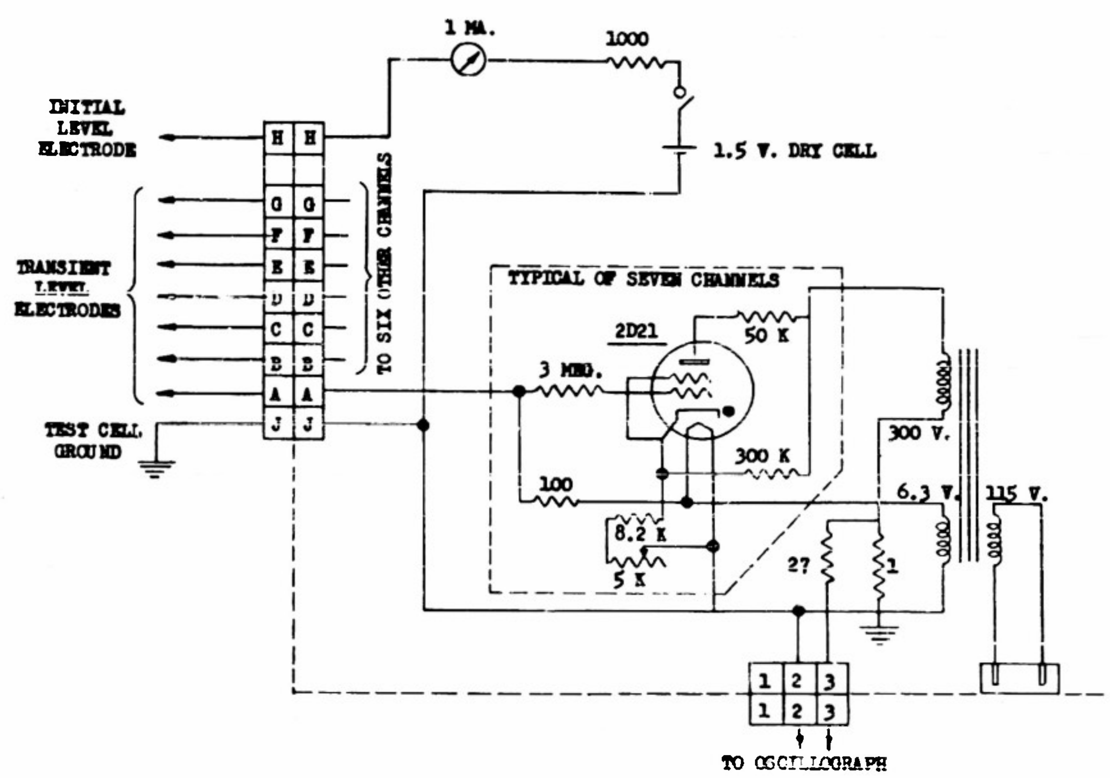


Figure 14. Circuit Diagram of Ballast Level Indicator

A circuit diagram of the ballast level indicator is shown in Figure 14. Also shown in this diagram is the direct current system used in conjunction with an eighth spark plug for setting the initial ballast level. The water level indicator with its seven 2D21 thyratrons can be seen at the front left corner of the bench in Figure 15.

Pressure and Pressure Differential

For recording the tank pressure a reluctance type pressure pickup was used in connection with a 2000-cycle carrier amplifier. The pickup was a Model 3PF3000 made by the Wiancko Engineering Corporation, and the amplifier

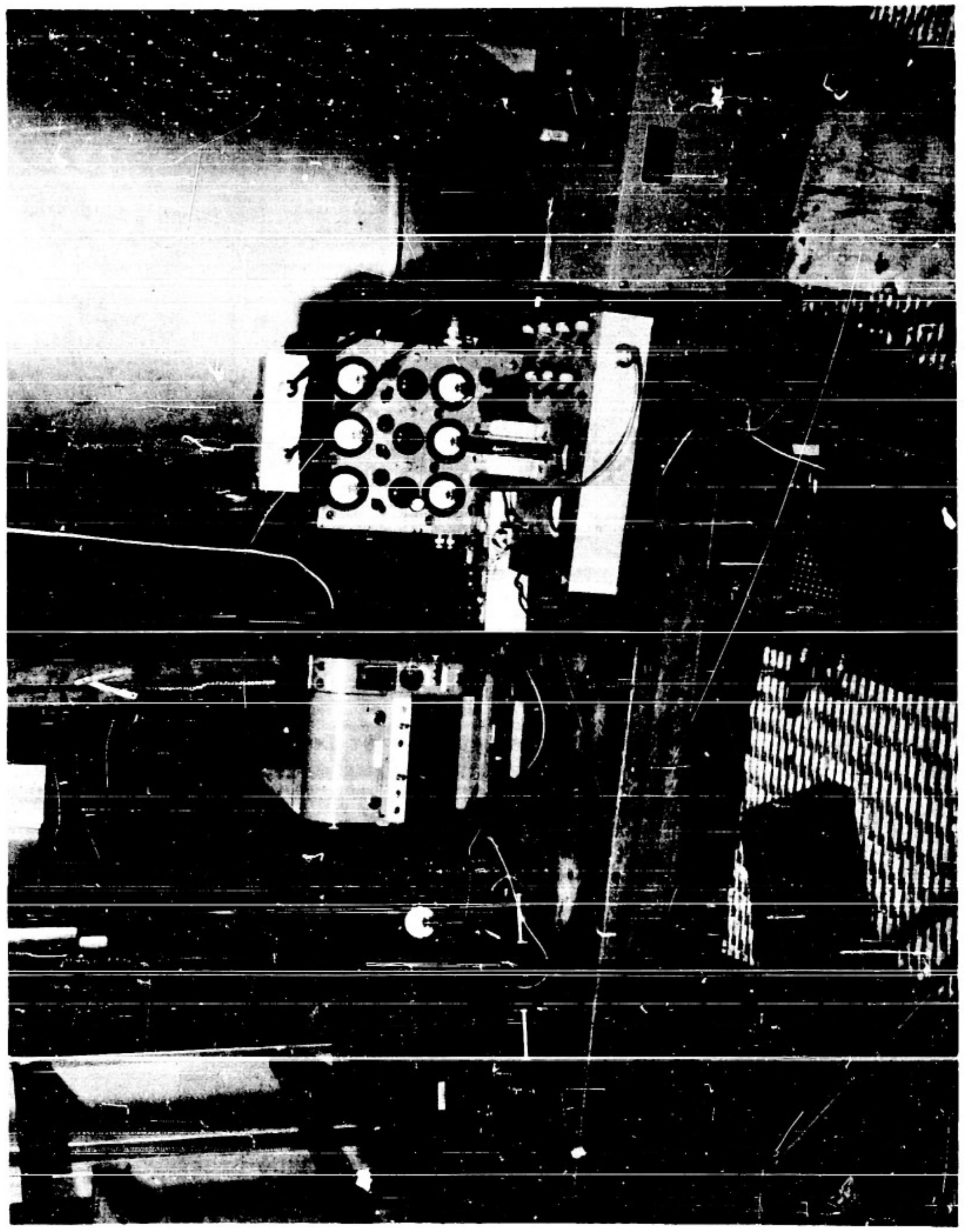


Figure 15. View of Recording Position

was a Model CD-2 made by the William Miller Corporation.

For measuring test cell pressure differential two 3PF3000 pressure gages were used, one connected to the pressure tank and the other to the test cell. As the differential pressure was the difference between these two pressures, the electrical outputs were connected in opposition through a network that equalized their sensitivities and linearities. With this network it was possible to reduce the indicated output to less than 1.5 psi over a

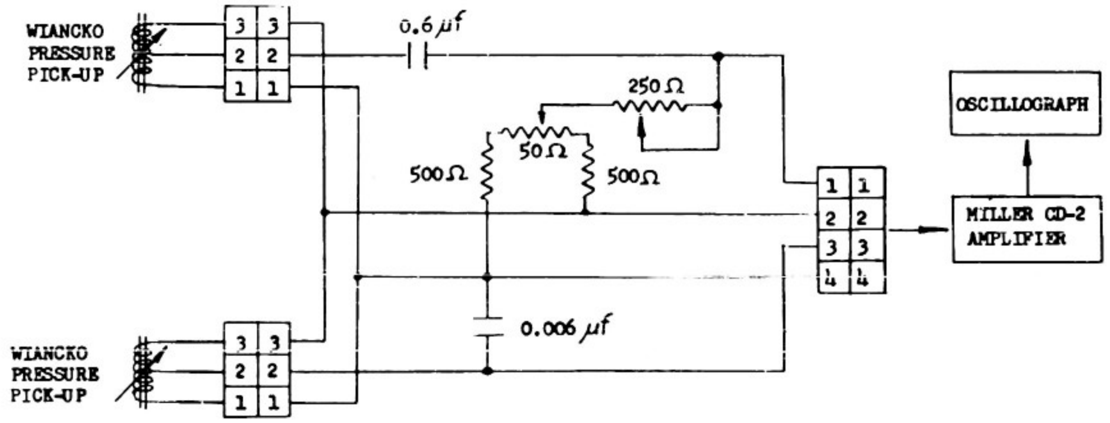


Figure 16. Equalizing Network of Differential Pressure Measurement

pressure range of zero to 1500 psi with no pressure differential. This was considered sufficiently good for an anticipated pressure differential of about 100 psi.

The pressure pickups can be seen at the left side of the pressure tank in Figure 7, while the Miller CD-2 amplifier with the equalizing circuit box on top of it is shown at the left rear of the bench in Figure 15. A circuit diagram of the equalizing network is shown in Figure 16.

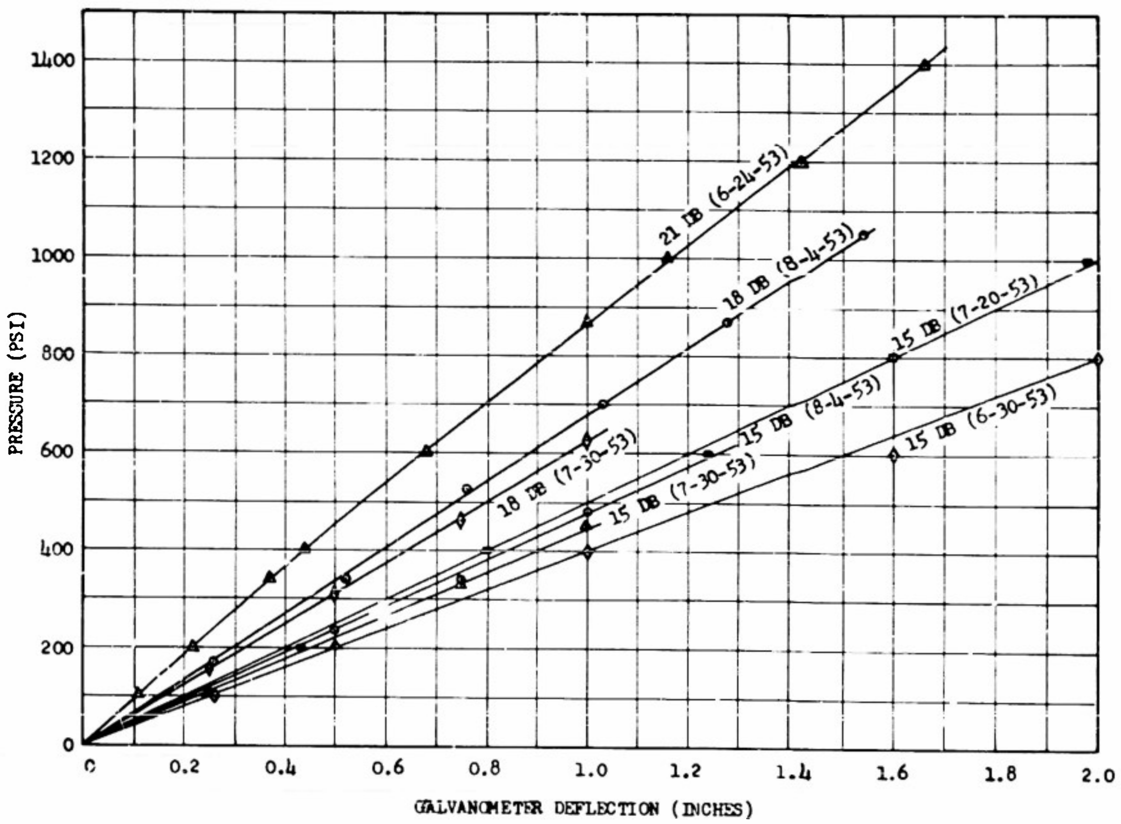


Figure 17. Calibration of Pressure Recording System

The pressure and pressure differential systems were calibrated with a dead load tester at several times during the period of the firings and, in the case of the pressure system, three different amplifier gains were used. These calibrations are shown in Figures 17 and 18. In addition, the pressure calibrations were checked against the galvanometer deflections obtained for known tank pressures at the time of firing. Although the calibrations vary somewhat from time to time for a given amplifier gain setting, each checks well with the value taken from the oscillograph record at the closest firing date. The actual calibrations used in the reduction of the data are shown in Table 5.

TABLE 5
PRESSURE AND TEMPERATURE CALIBRATIONS

Test No.	Pressure (psi/inch)	Pressure Differential (psi/inch)	Temperature of Insulation Surface (°F/inch)	Temperature of Calorimeter Block (°F/inch)
1	862	107	790	71
3	864	100	830	64
4	470	100	830	64
5	690	100	830	64

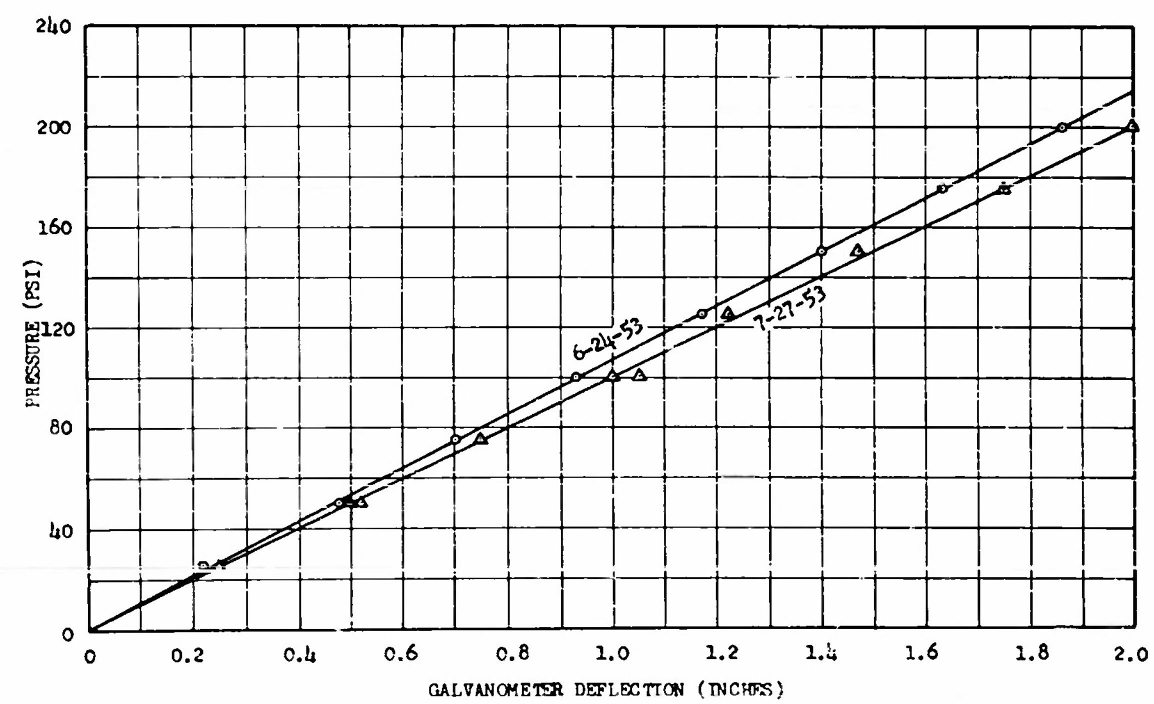


Figure 18. Calibration of Pressure Differential Recording System

Temperatures

Iron-constantan thermocouples were used in all four cases as the sensing elements, and except for the water jacket thermocouple outputs were used to actuate sensitive galvanometers directly through resistors to set the sensitivity and galvanometer damping characteristics. In the case of the water jacket, the thermocouple output was amplified with a Model 1A direct-current amplifier made by the William Miller Corporation.

Each of the four thermocouple systems for recording temperature was calibrated either before installation or with a second thermocouple of the same wire and size as the one installed. Calibration was accomplished using water and oil baths and mercury thermometers. The values used in data reduction are shown in Table 5.

Heat Flow

In order to determine the heat loss through the thermal insulation, an 8- by 8-inch slab of aluminum one inch thick and curved to fit the inside surface of the ballast chamber was used as a calorimeter block. It was insulated from the ballast chamber wall with a quarter-inch sheet of neoprene and covered on its inner face with Stabond HT-12 insulating material to the same thickness as the inner surface of the ballast chamber. The edges were heavily coated with HT-12 to eliminate edge effects.

It was realized that the calorimeter block would not remain at the same temperature as the aluminum skin, but since the difference would be small compared with the total temperature drop across the insulating material, it was neglected. The temperature rise of the block would then be a measure

of the total heat flow through the insulation. Using a specific heat capacity of 0.226 Btu/lbm °F and a density of 170 lbm/ft^3, the heat capacity of a one-inch slab of aluminum is computed to be 3.20 Btu/°F ft^2.

Although the rate of heat flow to the calorimeter block can be computed from the heat capacity if the average rate of temperature change of the block is known, it was desired to know what errors would occur for transient heat flow when the temperature of only one point is known, and what the optimum position for placing the thermocouple would be.

For the unidimensional case of a slab bounded by planes at $x = 0$ and $x = \ell$, with a constant heat flux into the solid at $x = \ell$, and no heat flow over $x = 0$, a solution is available (Reference 2) and is reproduced below.

$$T = \frac{Q\ell}{k}\left\{\frac{\alpha t}{\ell^2} + \frac{3x^2 - \ell^2}{6\ell^2} - \frac{2}{\pi^2}\sum_{n=1}^{\infty}\frac{(-1)^n}{n^2}\, e^{-\alpha n^2\pi^2 t/\ell^2}\cos n\pi x/\ell\right\}$$

where

T = temperature

Q = heat flux (Q is used later for total heat flow)

k = thermal conductivity

α = thermal diffusivity

Using $\alpha = 0.122 \frac{in.^2}{sec}$ and ℓ = one inch, the above expression has been evaluated for $\frac{k}{Q\ell} T$ at $x = 0$, $x = \ell/2$, and $x = \ell$. The results are shown in Figure 19.

Examination of these curves indicates that at $x = 0$ or $x = \ell$ the time required for the rate of change of temperature to approach a constant value is fairly long but is much shorter for $x = \ell/2$. It was estimated that an optimum

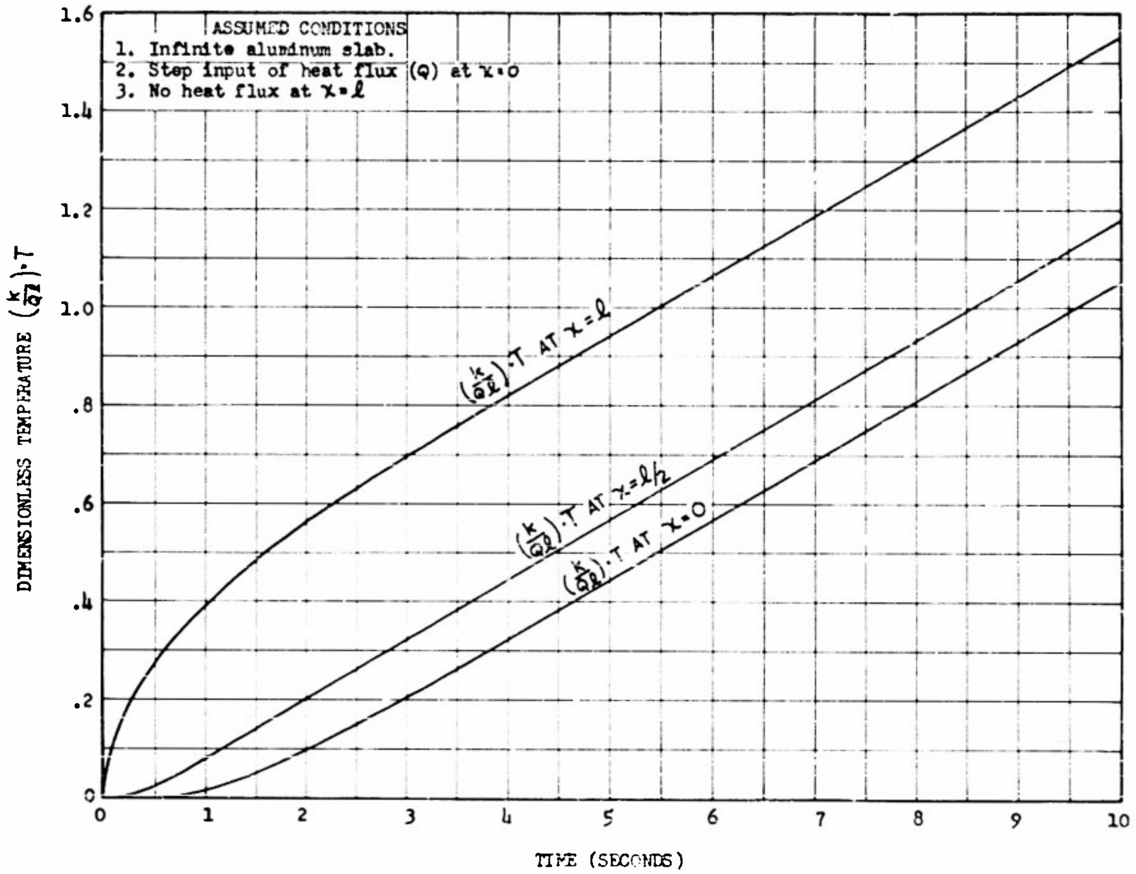


Figure 19. Dimensionless Temperatures in Calorimeter Block

position for measuring the temperature would be at $x = 0.6\ell$, and on the basis of this approximation, a thermocouple was placed in the calorimeter block at six-tenths of the distance from its outer to its inner face.

The Firing System

The firing system was designed to test individually up to seven ignitors for deviations from their normal resistance and to fire them all simultaneously. In addition, it was desired that the ignitors be kept shorted at all times except just prior to firing.

Figure 20. Instrumentation at Remote Control Position

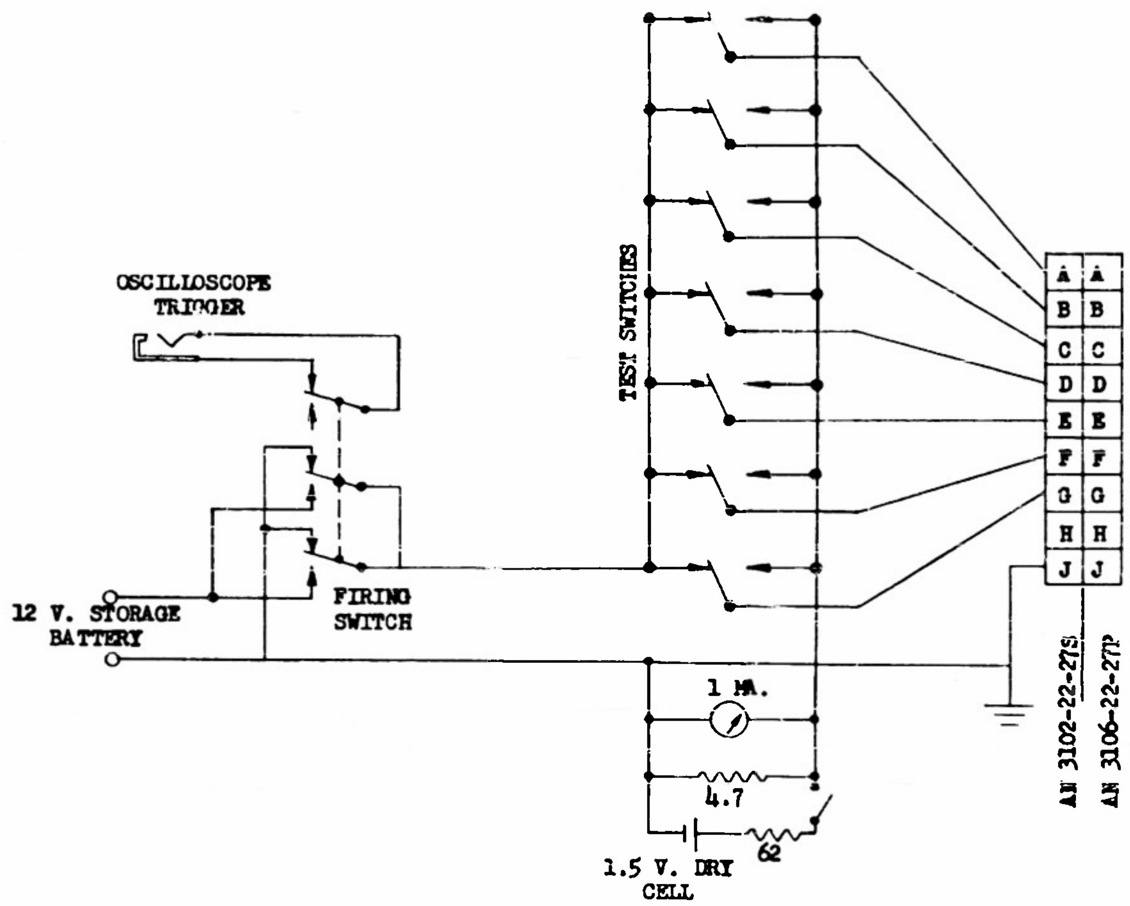


Figure 21. Circuit Diagram of Firing Box

This system can best be described by starting with the ignitor leads (Figure 11), which were terminated with a stacking type of dual banana plug, which in turn could be kept shorted until after it had been plugged into one of seven positions in an ignitor panel. From this panel the ignitor cable led to the remote control position and ended in an AN connector to which could be connected either a shorted connector or the firing box. In addition to

testing and firing functions this box served to initiate a "single sweep" of the oscilloscope used with the Rutishauser pressure indicating system as described earlier. The firing box can be seen at the right front of the bench in Figure 20 with the associated fuses and batteries below it and to the right, and with the shorted cable end to the left. For a circuit diagram of the box, refer to Figure 21.

TEST NO. 1

With the test cell in place in the pressure tank, the following procedure was followed for Test No. 1. A total of 220 gallons of water containing 125 pounds of salt was added to the tank, and the water jacket was filled as far as possible without the bulkhead in place. One gas generator was attached to the center of the bulkhead which was then bolted in place. After checking the firing system to make sure that the shorting plug was in place at the remote control position and that a short was indicated at the ignitor plug-in panel, the ignitor was placed in the generator. The water jacket was then filled to cover the bulkhead with about three inches of water. The firing system was rechecked, the ignitor leads plugged into the ignitor panel, and the shorting plug removed from the ignitor leads. The lid was put on the pressure tank and locked in place.

In order to remove as much air as practicable from the test cell and pressure tank, one cylinder of nigrogen was used to pressurize the tank, all gas was vented from the test cell, and the tank was vented to atmospheric pressure. Nitrogen was then added to the test cell to lower the ballast to the bottom of the cell and thus give an opportunity to check the water level

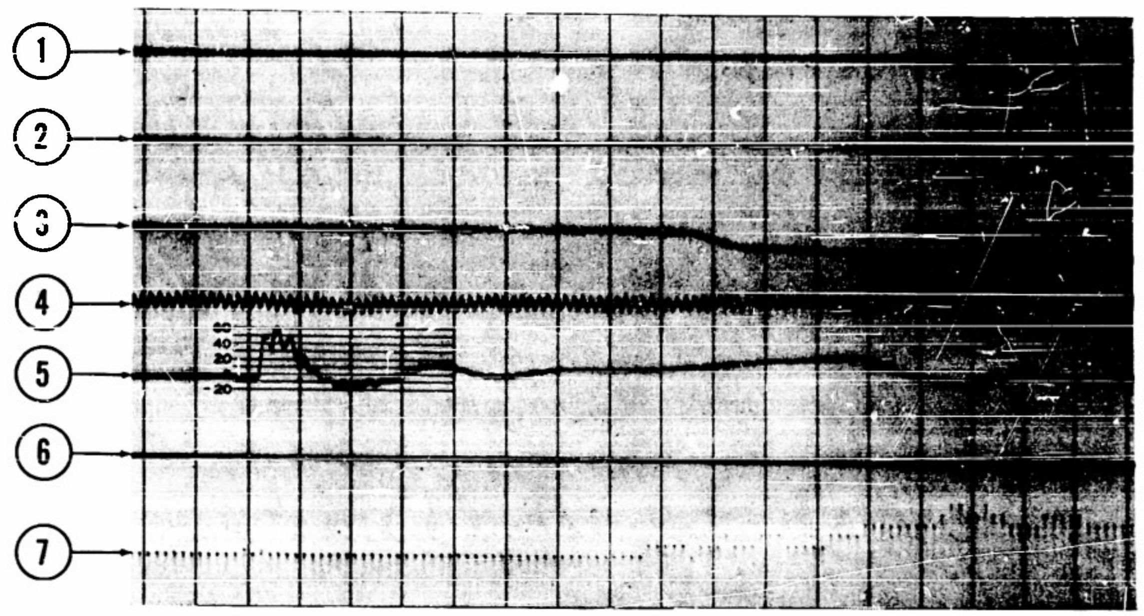
indicating system as the tank pressure was increased to 210 psi and the ballast brought to its proper initial level.

After all personnel had retired to the remote control position, the firing procedure was begun. The shorting plug was removed from the firing cable, the cable was connected to the firing box, the ignitors tested for normal resistance, and the fuses placed in the power leads to the box. A count-down from ten was used to sequence the various operations from this point on. The camera shutter was opened at "four," the oscillograph started at "three," and the firing and motor valve switches closed at "one."

After 30 seconds the oscillograph was turned off, the ignitor resistance checked for indications of firing, and the shorting plug placed on the ignitor cable. When the tank pressure had dropped to near atmospheric as indicated by the dial gage at the remote control position, it was considered safe to leave the shelter and approach the tank. The test cell was flooded and the tank then purged with one cylinder of nitrogen to remove most of the noxious combustion gases.

When the tank was opened the test cell was structurally intact. The surface of the insulating material was found to be quite dark in some areas but this was apparently caused by combustion products from the gas and not by charring of the insulation.

The oscillograph record made during Test No. 1 is shown in Figure 22. Data taken from this record showed a peak ballast chamber pressure differential of 61 psi, a tank pressure rise from 210 to 263 psi, and indicated that the ballast ejection process had not been carried quite far enough. It was decided



1. TEMPERATURE OF CALORIMETER BLOCK
2. TEMPERATURE OF BALLAST CHAMBER SKIN
3. TEMPERATURE OF INSULATION SURFACE
4. TEMPERATURE OF WATER JACKET
5. PRESSURE DIFFERENTIAL ACROSS BALLAST CHAMBER WALL
6. TANK PRESSURE
7. BALLAST DISPLACEMENT

Figure 22. Oscillograph Record of Test No. 1

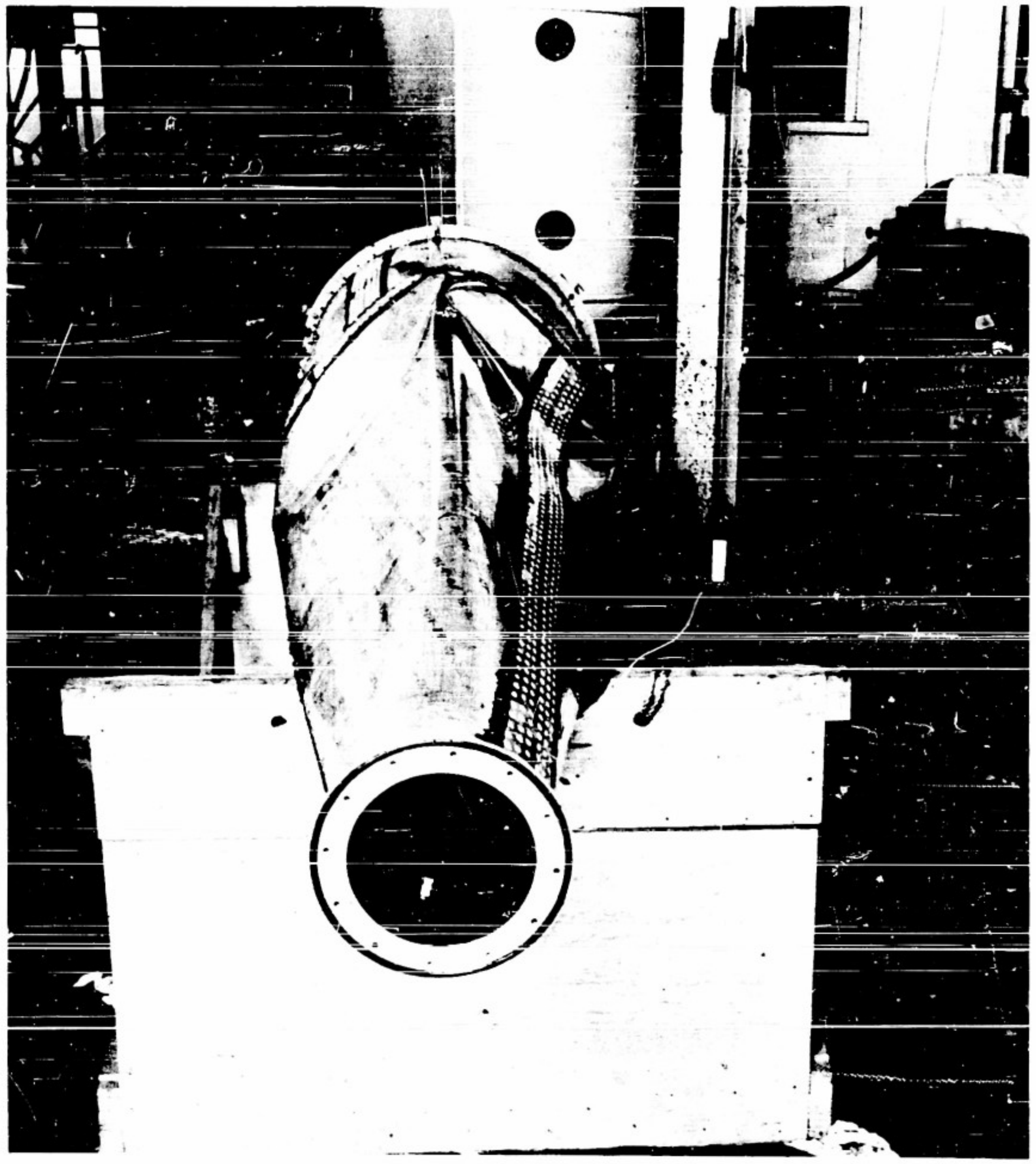


Figure 23. First Ballast Chamber After Test No. 2

that the amount of propellant used was close enough to the correct value to yield significant data and that it was safe to make a test, at a higher pressure, using two gas generators.

TEST NO. 2

The test cell was washed out, dried, and the insulating material recoated with Stabond C-111. This test was conducted in the same manner as Test No. 1 except that two gas generators were used and the initial pressure was 400 psi.

When the pressure tank was opened it was found that one of the tension rods had failed, that the ballast chamber had buckled, and that the bottom plate of each of the gas diffusers was missing because of erosion of metal near the bottom of the outlet holes. Damage to the ballast chamber and the diffusers is shown in Figures 23 and 24.

Analysis of the oscillograph record (Figure 25) showed peak ballast chamber pressure differentials of 127 psi from inside out, and 32 psi from outside in. The tank pressure rise was from 400 to 483 psi. Subsequent stress analysis showed that the negative pressure peak of 32 psi was more than enough to crush the ballast chamber. It was concluded that diffuser failure had allowed the rocket motor jet streams to "drill" holes through the water ballast and thus allow the pressure differential to drop to near zero at a time when the remaining ballast had considerable exit velocity. When the motors were through burning and the "holes" closed, the inertia of the ballast caused a negative pressure surge which crushed the chamber. Failure of the tension rod was found to have resulted from a centering hole used in machining the rod. It

was deci..ed that no useful data could be obtained from this test and that another test using two gas generators should be conducted.

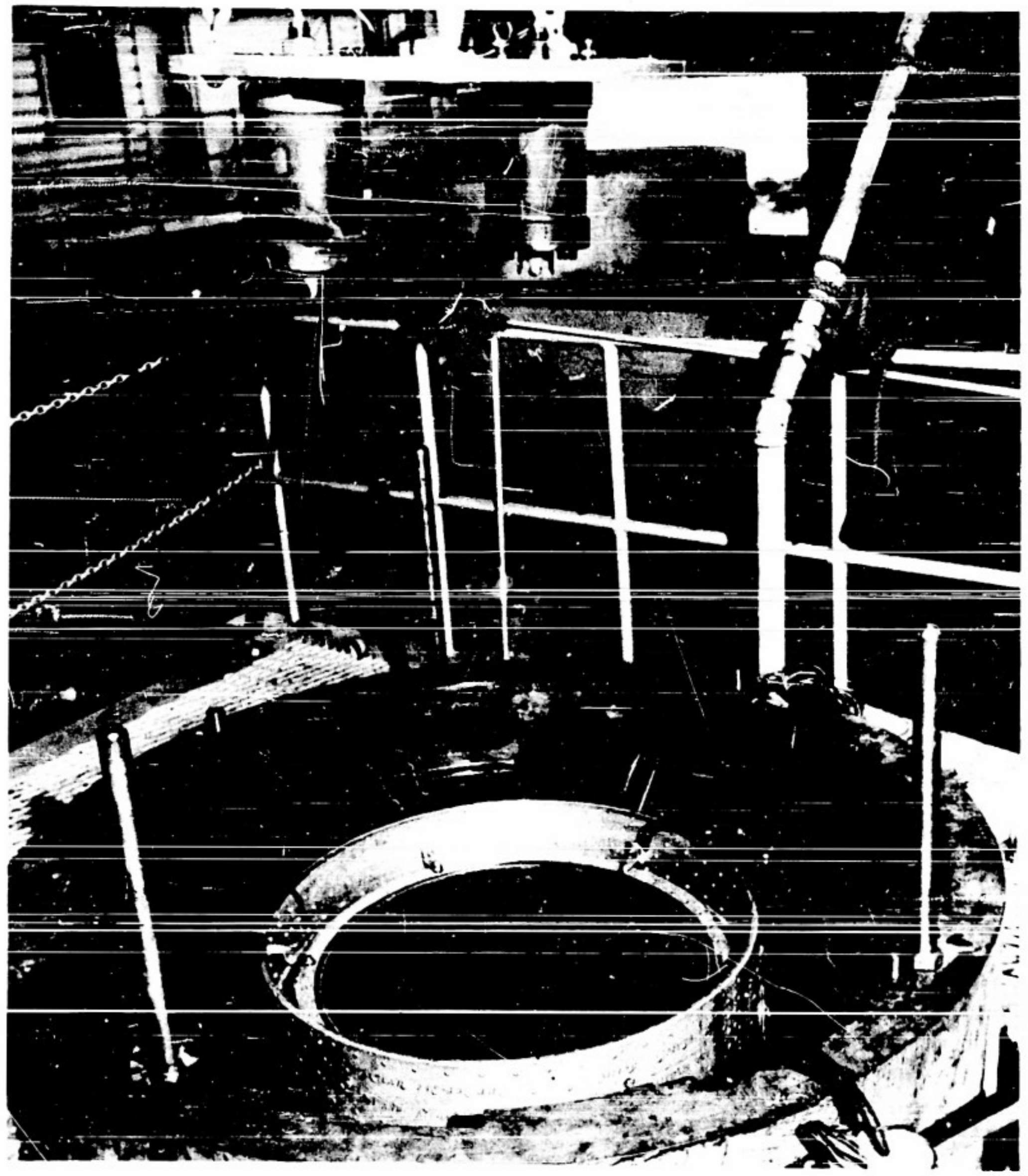
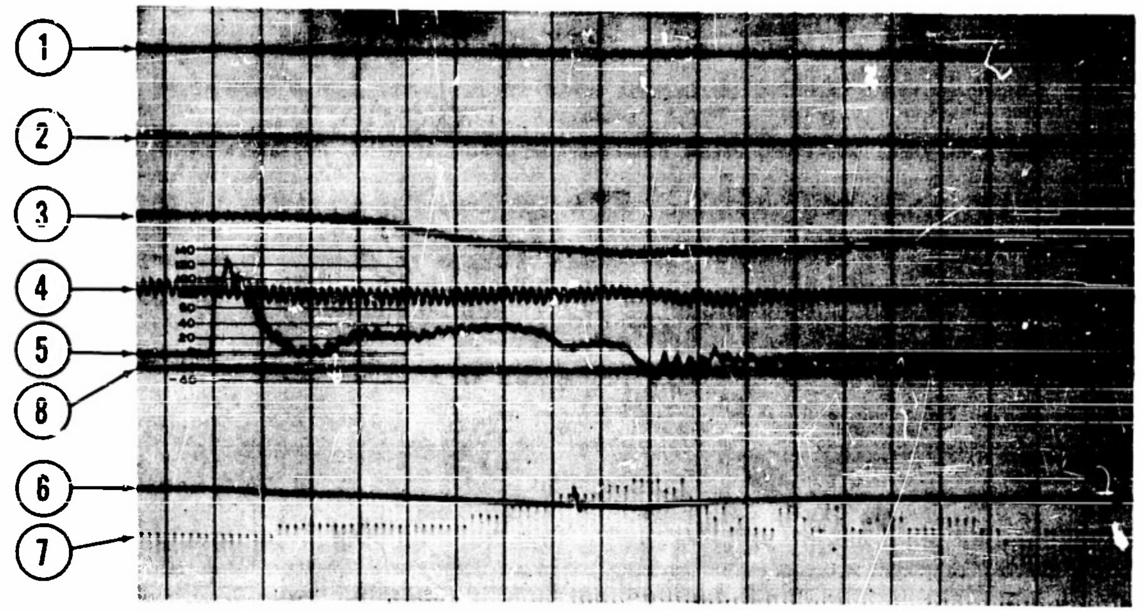


Figure 24. View of Gas Generators After Firing in Test No. 2



1. TEMPERATURE OF CALORIMETER BLOCK
2. TEMPERATURE OF BALLAST CHAMBER SKIN
3. TEMPERATURE OF INSULATION SURFACE
4. TEMPERATURE OF WATER JACKET
5. PRESSURE DIFFERENTIAL ACROSS BALLAST CHAMBER WALL
6. TANK PRESSURE
7. BALLAST DISPLACEMENT
8. REFERENCE TRACE

Figure 25. Oscillograph Record of Test No. 2

TEST NO. 3

Because of the failure encountered in Test No. 2 certain design changes were incorporated into the equipment used in Test No. 3 and subsequent tests. A second test cell was completed with the ballast chamber reinforced with rings (Figure 26), which were designed to furnish crushing stability up to a pressure of 50 psi. The diffuser design was changed to prevent burn-through and to allow a somewhat more free gas flow. The new diffuser design, and the region of failure in the old one, are shown in Figure 27.

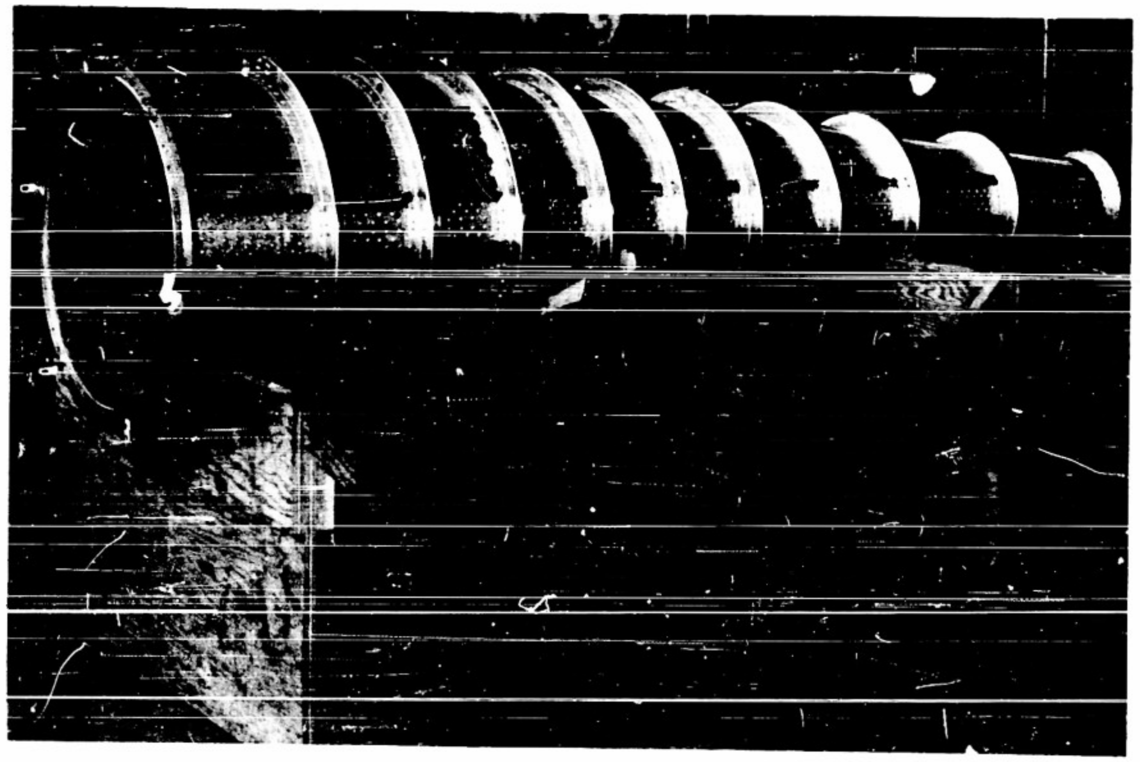


Figure 26. Second Ballast Chamber Showing Reinforcing Rings

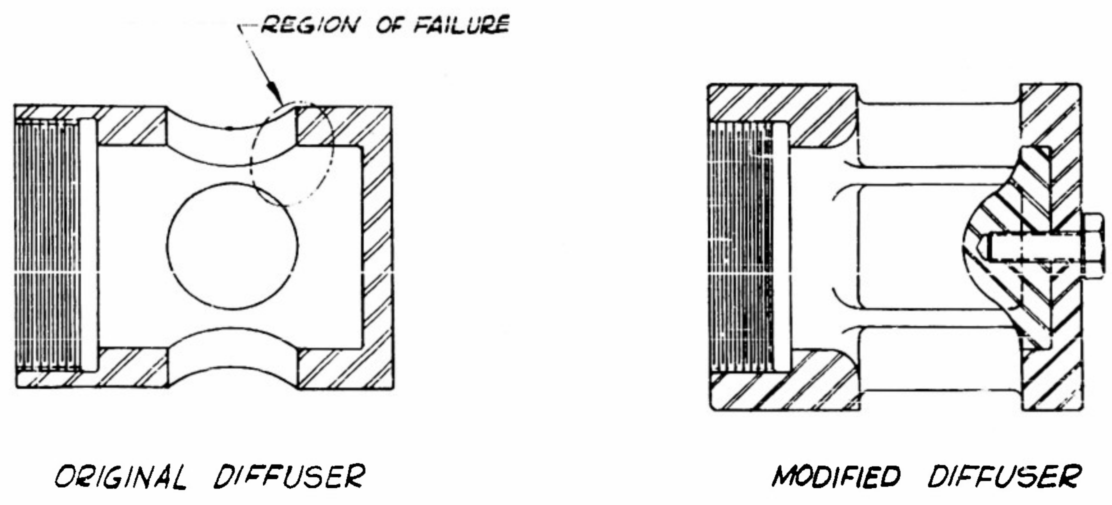
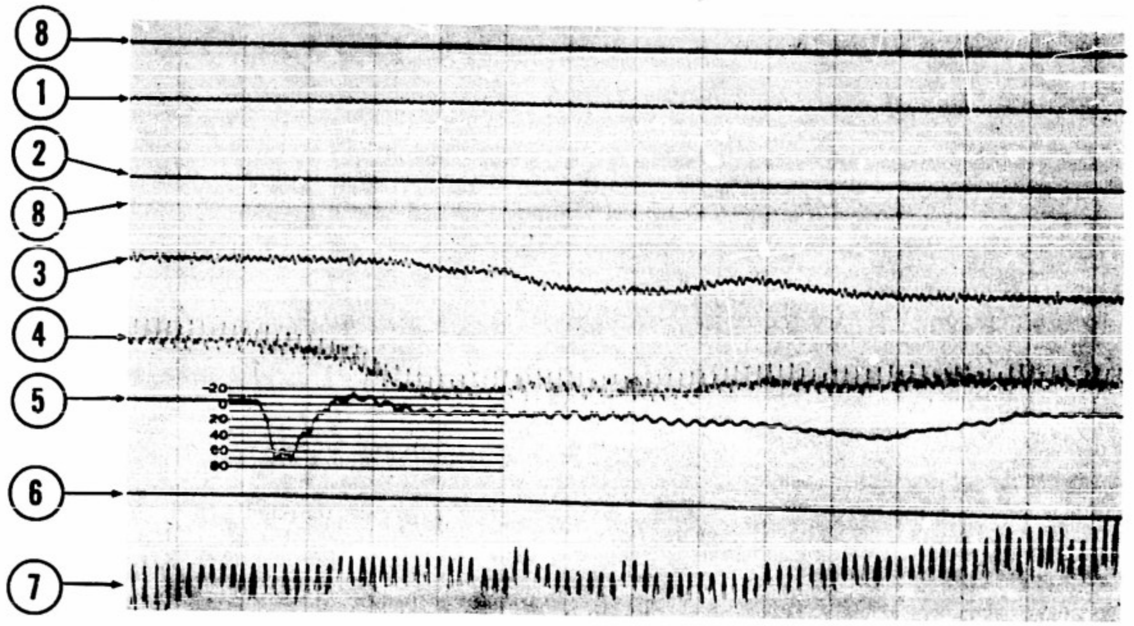


Figure 27. Original and Modified Diffusers

The test was conducted in the same manner as Test No. 2, using two gas generators, except that the initial pressure was 415 psi and the motor actuated valve on the pressure tank failed to open when desired. The oscillograph record (Figure 28) showed a peak pressure differential of 71 psi, a tank pressure rise to 528 psi, and indicated that the ballast ejection process was fairly complete. Slight local charring of the insulation occurred but was not considered serious.

In spite of the failure of the motor-valve, Test No. 3 was quite satisfactory from a pressure standpoint and the amount of propellant used appeared to be very near the optimum value. It was concluded that a test using three gas generators with an initial tank pressure in the vicinity of 600 psi could be safely carried out.

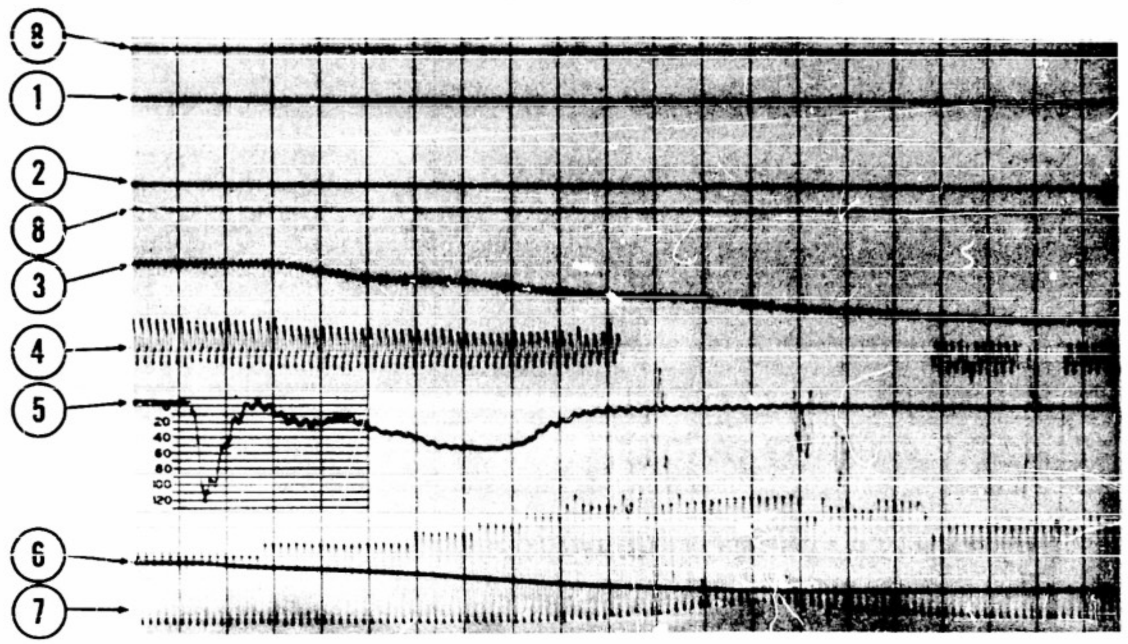


1. TEMPERATURE OF CALORIMETER BLOCK
2. TEMPERATURE OF BALLAST CHAMBER SKIN
3. TEMPERATURE OF INSULATION SURFACE
4. TEMPERATURE OF WATER JACKET
5. PRESSURE DIFFERENTIAL ACROSS BALLAST CHAMBER WALL
6. TANK PRESSURE
7. BALLAST DISPLACEMENT
8. REFERENCE TRACE

Figure 28. Oscillograph Record of Test No. 3

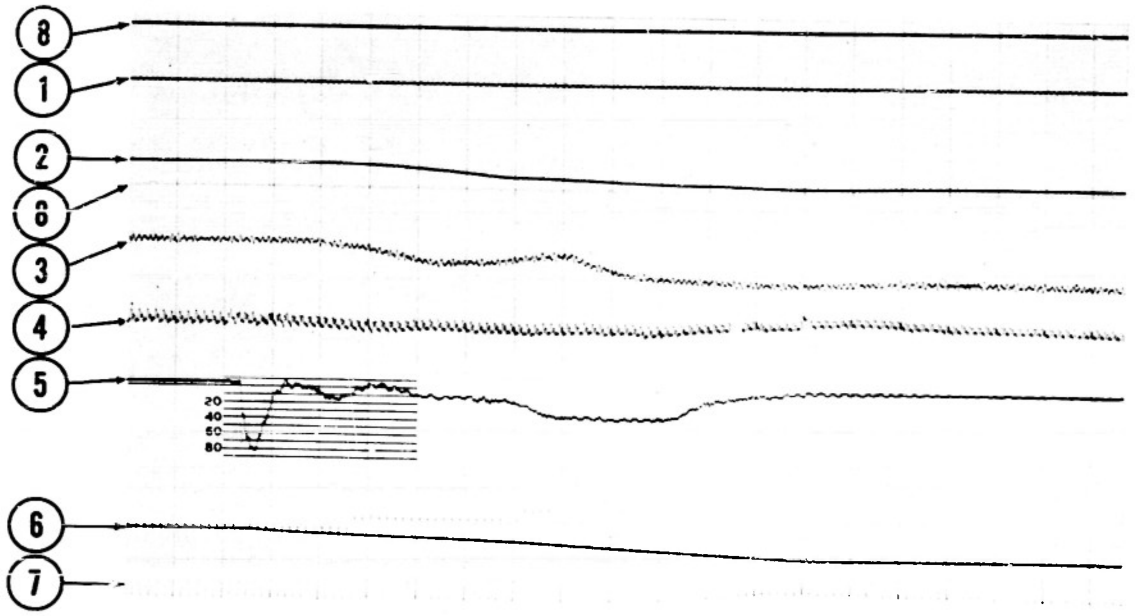
TEST NO. 4

This test was conducted with the same equipment and in the same manner as Test No. 3 except that three gas generators were used and the initial pressure was 615 psi. The oscillograph record (Figure 29) showed the rather



1. TEMPERATURE OF CALORIMETER BLOCK
2. TEMPERATURE OF BALLAST CHAMBER SKIN
3. TEMPERATURE OF INSULATION SURFACE
4. TEMPERATURE OF WATER JACKET
5. PRESSURE DIFFERENTIAL ACROSS BALLAST CHAMBER WALL
6. TANK PRESSURE
7. BALLAST DISPLACEMENT
8. REFERENCE TRACE

Figure 29. Oscillograph Record of Test No. 4



1 TEMPERATURE OF CALORIMETER BLOCK
2 TEMPERATURE OF BALLAST CHAMBER SKIN
3 TEMPERATURE OF INSULATION SURFACE
4 TEMPERATURE OF WATER JACKET
5 PRESSURE DIFFERENTIAL ACROSS BALLAST CHAMBER WALL
6 TANK PRESSURE
7 BALLAST DISPLACEMENT
8 REFERENCE TRACE

Figure 30. Oscillograph Record of Test No. 5

high peak pressure differential of 122 psi and indicated a considerable propellant excess over that required for complete ballast ejection at an initial pressure of 615 psi. Extensive charring of the Stabond HT-12 insulating material occurred in the upper two feet of the ballast chamber.

TEST NO. 5

After the insulating material that had been damaged in the previous test had been repaired, Test No. 5 was made, essentially a repetition of Test No. 4 except that the initial pressure was increased to 809 psi. The motor actuated valve failed to operate but this was not considered as detrimental

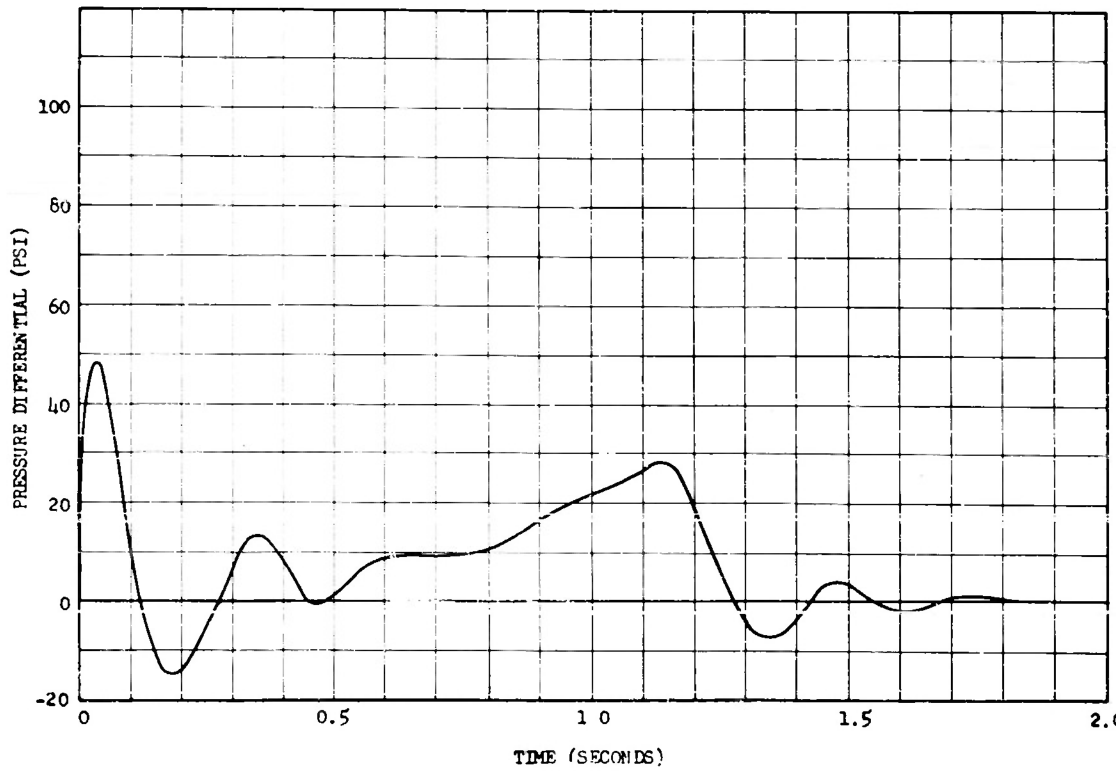


Figure 31. Pressure Differential Across Ballast Chamber in Test No. 1

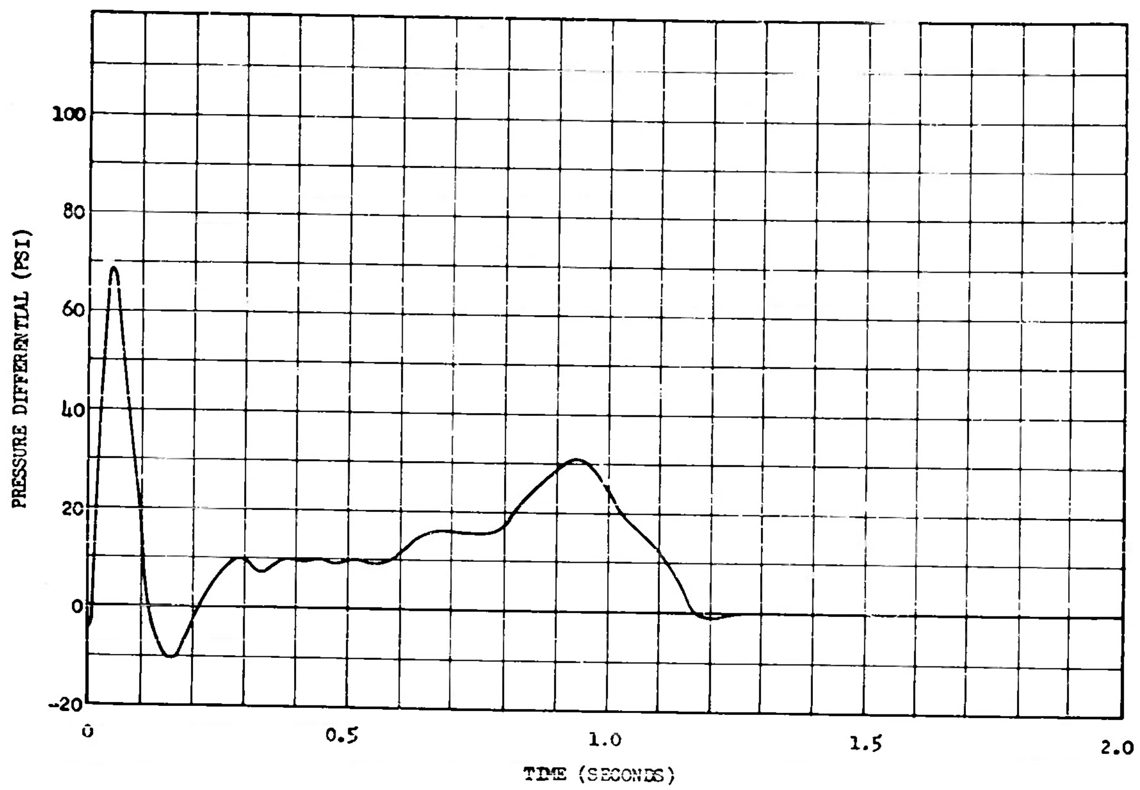


Figure 32. Pressure Differential Across Ballast Chamber Wall in Test No. 3

to the data. The oscillograph record (Figure 30) showed a peak pressure differential of 82 psi, a peak tank pressure of 1020 psi, and indicated that only a slight propellant excess existed over that required for complete ballast ejection. Charring of the insulating material was quite general in the upper portions of the ballast chamber.

Since the peak tank pressure was slightly over the limit set by NEL, there was no possibility of making a test using four gas generators and the ballast ejection tests were concluded with Test No. 5.

DATA

The oscillograph records of the ballast ejection tests extended over a period of several seconds before and about 30 seconds after each firing, and cannot be conveniently reproduced in this report because of their length. The information taken from these records is presented in Figures 31 through 41.

The measurements taken on ballast level were the discrete level indications from the spark plugs, and the curves shown in Figures 36 to 39 inclusive were drawn by connecting these points on the oscillograph records. These curves probably have very little significance in the first few seconds of

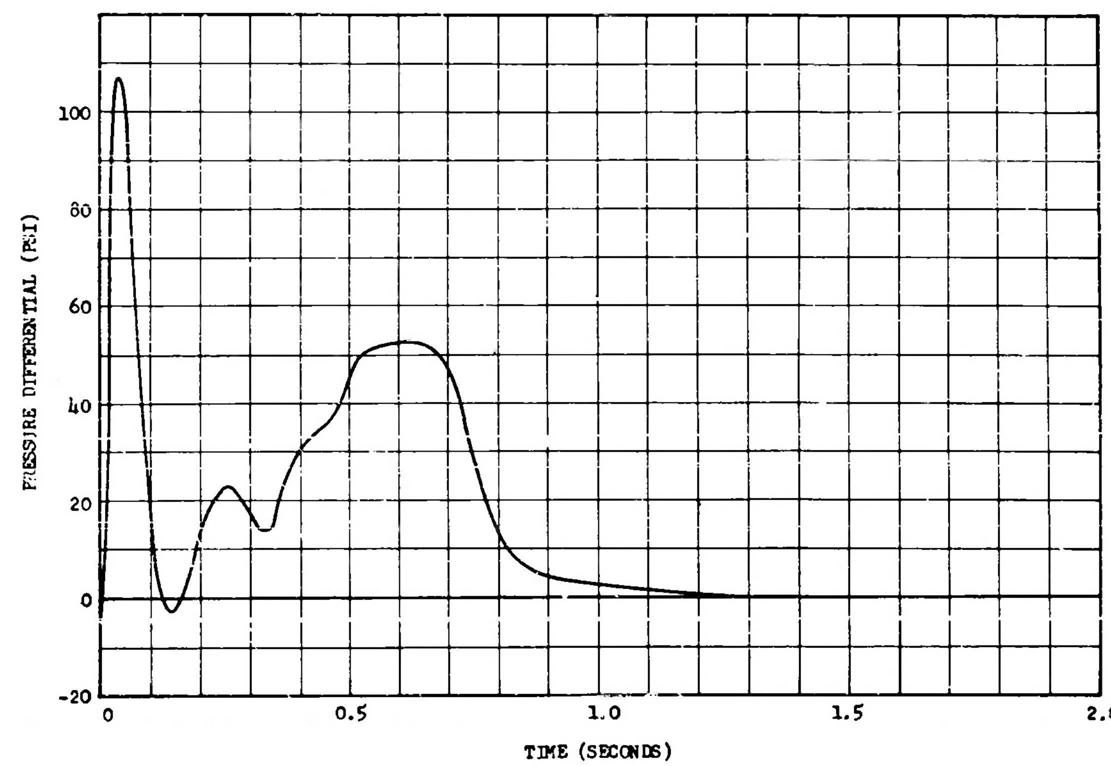


Figure 33. Pressure Differential Across Ballast Chamber Wall in Test No. 4

each test since the ballast surface was undoubtedly highly turbulent during this period.

The pressure differential data has been smoothed by neglecting the higher frequency components which are principally near 40 and 120 cycles per second. These components were neither predicted by the pre-test analysis nor have they been satisfactorily explained, and for present purposes will be neglected.

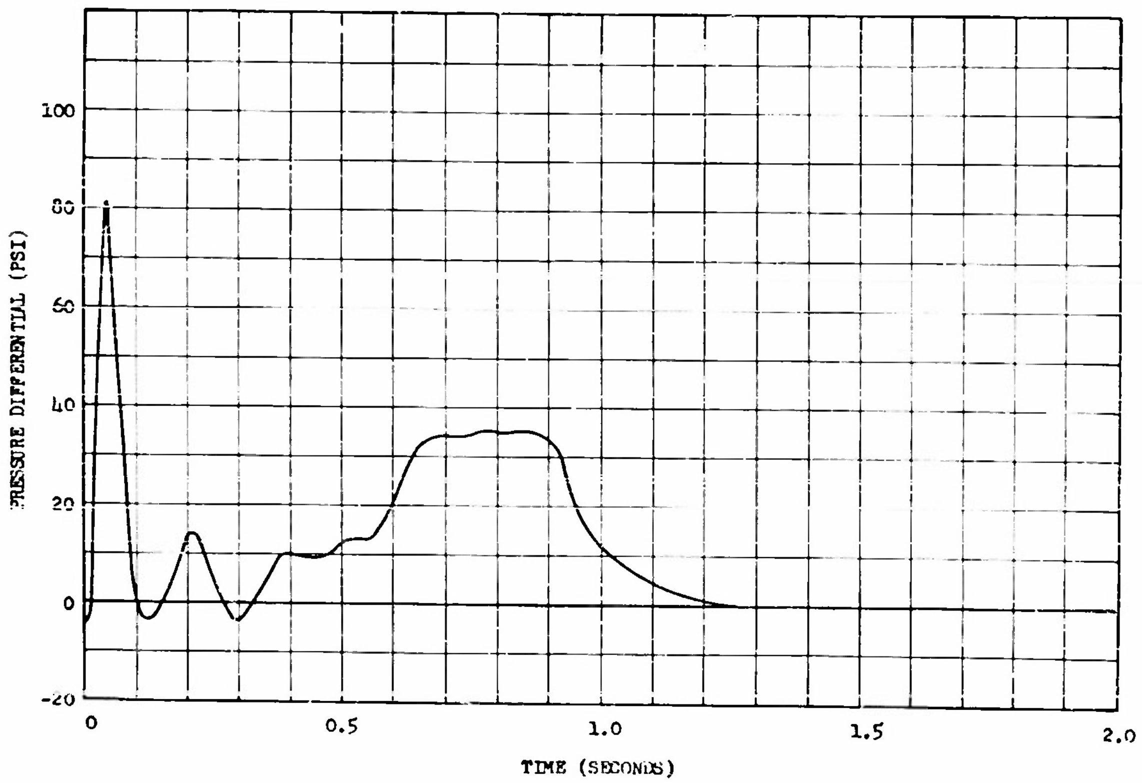


Figure 34. Pressure Differential Across Ballast Chamber Wall in Test No. 5

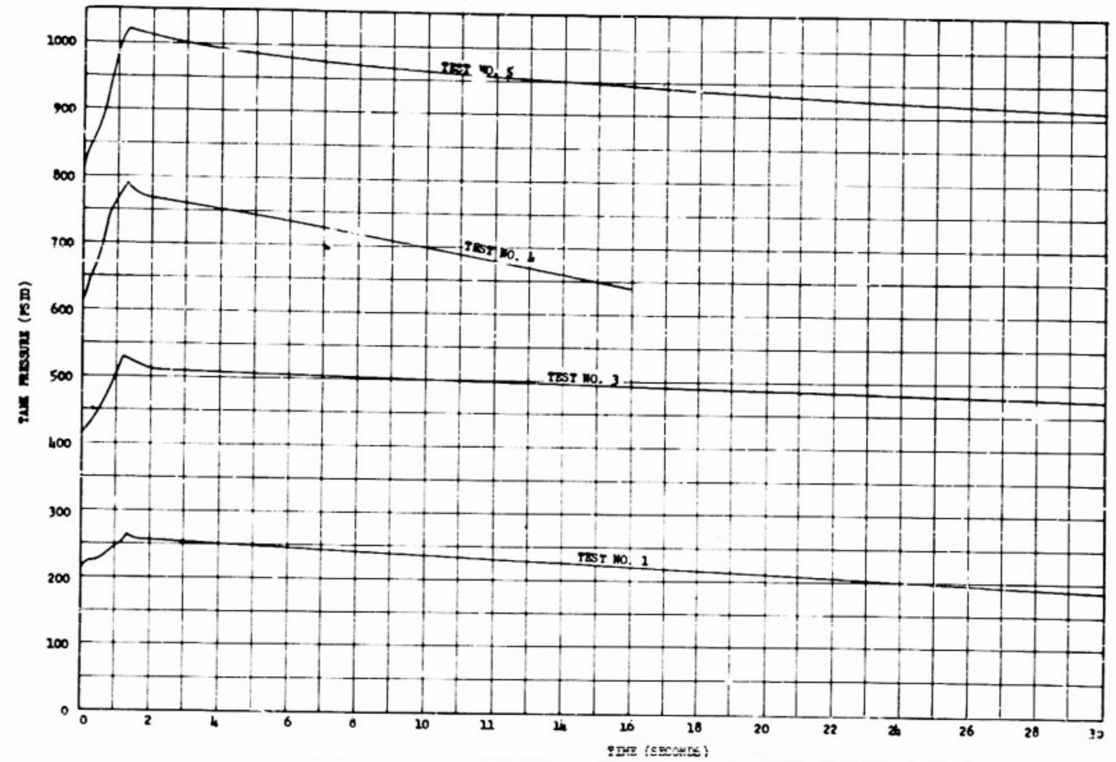


Figure 35. Tank Pressures Recorded in Ballast Ejection Tests

Of the four temperature recordings, it was necessary to discard that of the aluminum skin because of failure of the corresponding galvanometer, and that of the water jacket because of drift in the d-c amplifier.

In addition to the oscillograph records, there are listed in Table 6 the best estimates of the true tank pressure at the time of firing as indicated by the several dial gages connected to the tank.

TABLE 6
INITIAL PRESSURES

Test No.	Initial Pressure (psi)
1	210
3	415
4	615
5	809

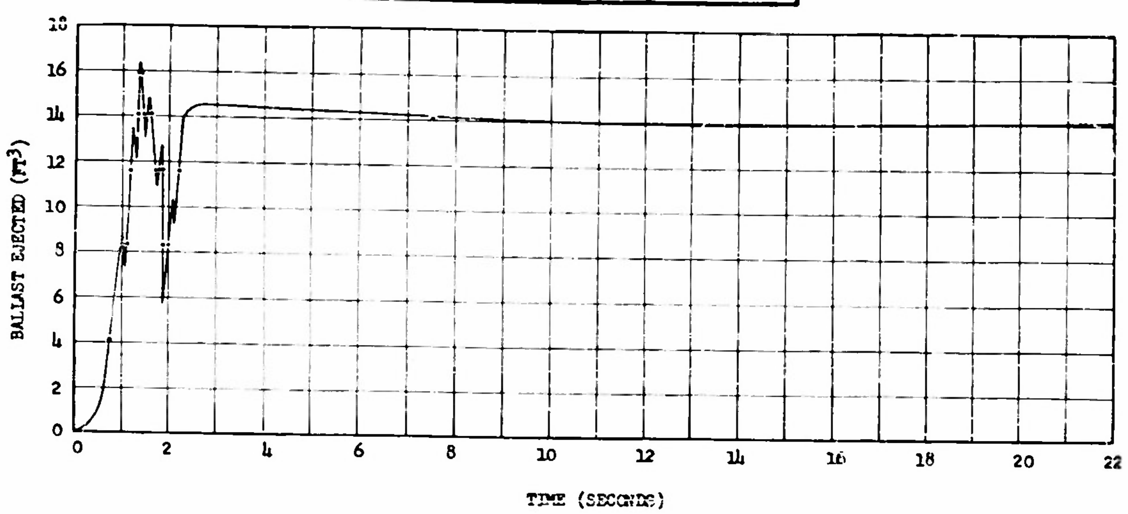


Figure 36. Ballast Displacement in Test No. 1

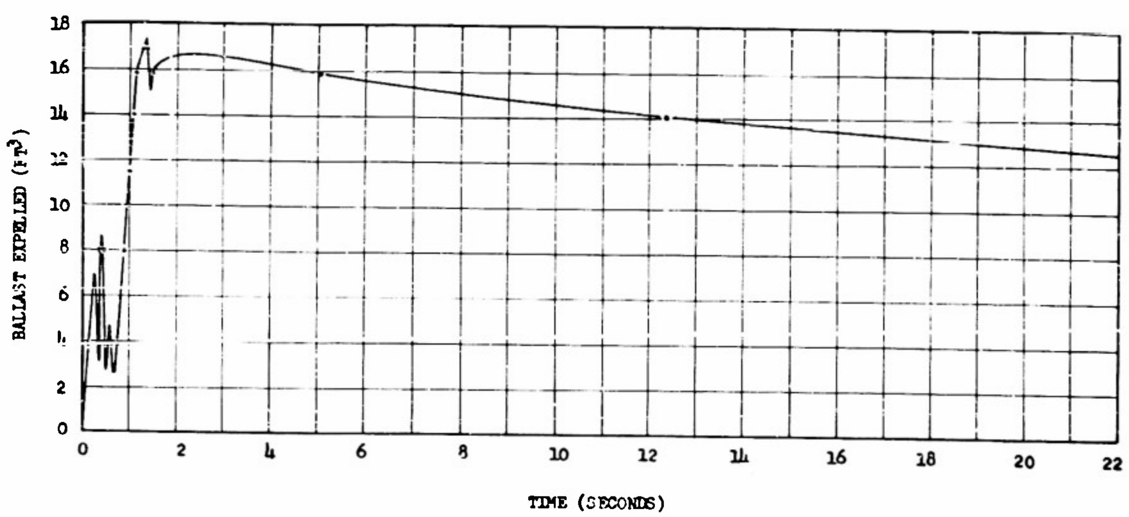


Figure 37. Ballast Displacement in Test No. 3

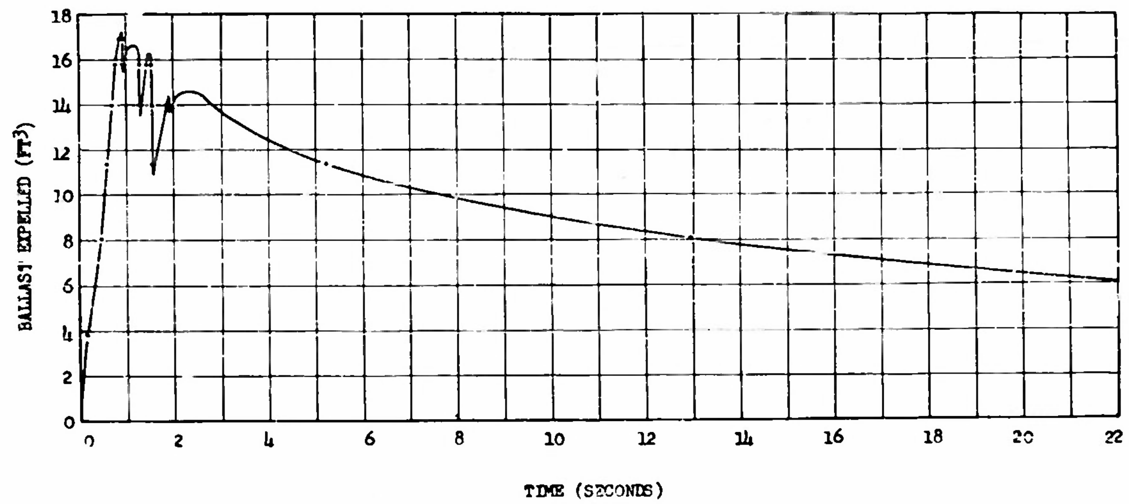


Figure 38. Ballast Displacement in Test No. 4

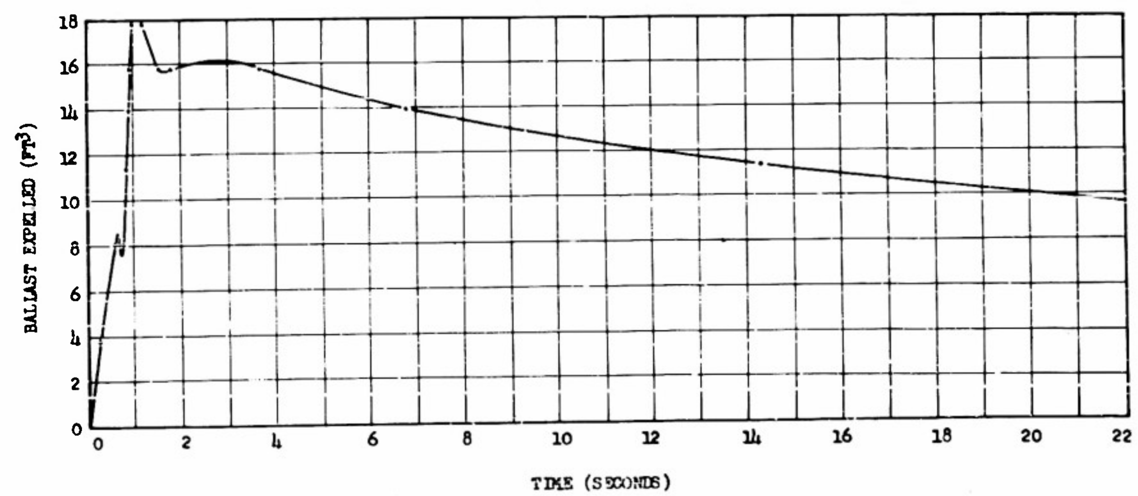


Figure 39. Ballast Displacement in Test No. 5

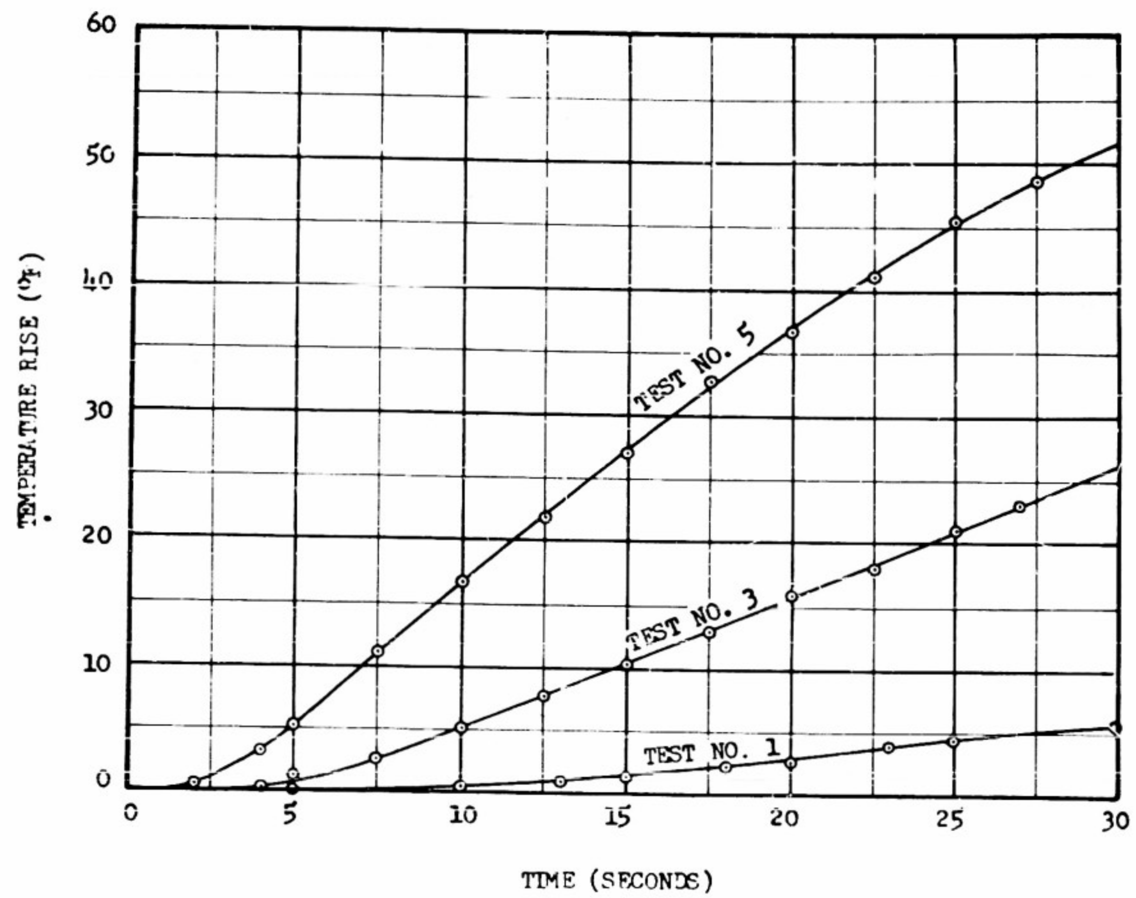


Figure 40. Temperature Rise of Calorimeter Block

DATA ANALYSIS

Ballast Ejection

Each of the tests was conducted using as nearly as possible the correct amount of propellant based upon the pre-test analysis and the results of the previous tests. The data was examined for some method that could be used in determining what the propellant excess or deficiency was in each case. The peak differential pressure seemed to offer n. possibilities for correlating

the various data, probably because of the variations in burning characteristics of the motors as well as slight variations in the ignition times of the several motors used in a single firing. The water level indications were too variable during the period of expulsion to be used in determining the time at which complete expulsion might have occurred.

The pressure differential curves (Figures 31 through 34) show that there is a high pressure peak at about 0.04 second, a few oscillations, and a rise to a fairly high value in the region of 0.5 to 1.2 seconds. At the end of this pressure rise the pressure drops rather rapidly. Although it has not been possible to give a good explanation for the exact ti-- at which this

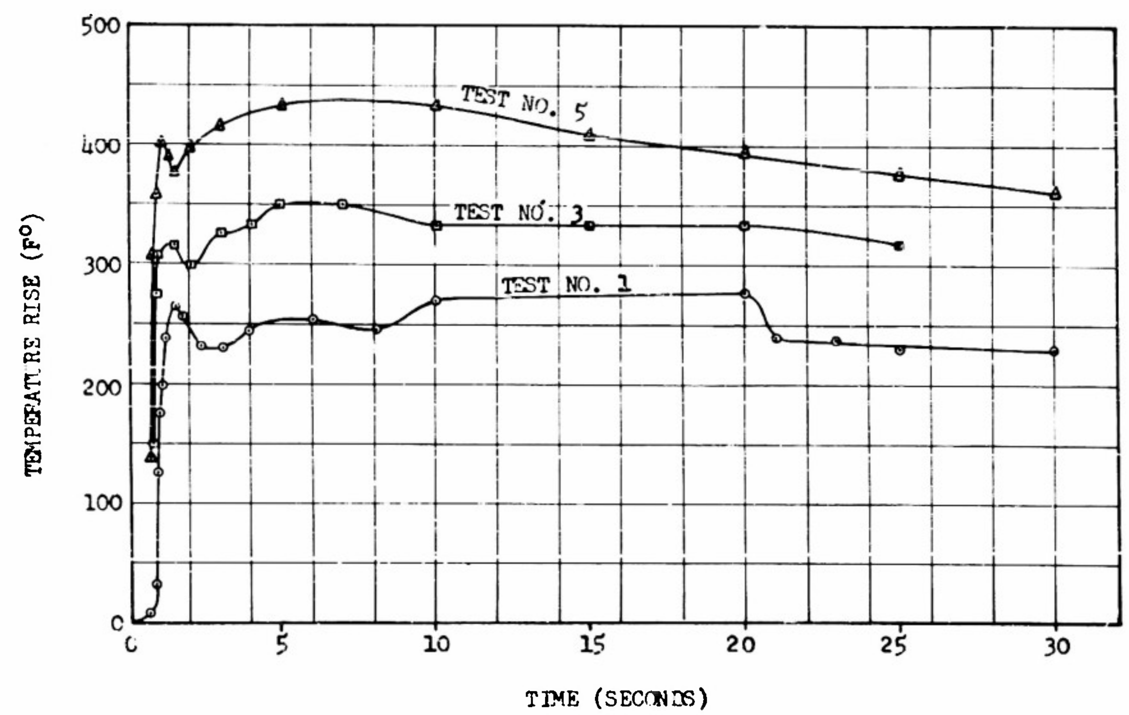


Figure 41. Temperature Rise of Insulation Surface

pressure fall-off occurs, it seems probable that it has some fixed relationship to the extent to which the ejection process has proceeded, and that the time to this point is proportional to the propellant needed for ejection. For convenience this point will be taken at the time when the pressure is decreasing at 100 psi per second.

Another approach, which can be used only if an excess of gas did not exist, is to extrapolate the ballast level back to 1.2 seconds, and thus to determine directly the amount of ballast ejected. The amount of propellant used can then be corrected in inverse ratio to the amount of ballast ejected to obtain the propellant required for complete ejection.

In the tests where an excess of propellant was burned, the tank pressure certainly rose higher than it would have had the correct amount been used. The tank pressure that would have been obtained had the ballast just been ejected can be computed assuming adiabatic compression of the tank gas.

a. Initial gas space in pressure tank = 116.4 cubic feet

b. Decrease in tank gas space = 17.8 cubic feet

c. $c_p/c_v = \gamma = 1.4$ (for nitrogen)

$$\frac{P_2}{P_1} = \left(\frac{V_1}{V_2}\right)^{\gamma} = \left(\frac{116.4}{116.4 - 17.8}\right)^{1.4} = 1.262$$

These pressures (included in Table 7) are fairly close to those measured and will be used in each case instead of the experimental values.

Both the water level and pressure differential curves for Test No. 3 seem to indicate that nearly the correct amount of propellant was used, and

TABLE 7
ADJUSTMENT OF PROPELLANT WEIGHT REQUIRED FOR OPTIMUM BALLAST EJECTION

	From Press. Diff. Data		From Ballast Ejection Data	
Test No.	Time of Press. Diff. Fall-off (sec.)	Propellant Weight Correction Factor	Ballast Ejected ft^3	Propellant Weight Correction Factor
1	1.16	1.21	14.7	1.21
3	0.96	1.00	17.8	1.00
5	0.905	0.94	-	-
Test No.	Initial Tank Pressure (psi)	Tank Pressure for Complete Ejection (psi)	Propellant Used (lb)	Propellant Needed (lb)
1	210	265	6	7.26
3	415	523	12	12.00
5	809	1020	18	16.96

since no better information is available it will be assumed to be optimum. Test No. 4 will be omitted from the analysis because of the large excess of propellant, and because a firing with three motors was repeated as Test No. 5 at a higher pressure.

Table 7 shows the various figures and correction factors used in obtaining the required propellant weights from those actually used in the tests. It should be noted that the same factor is obtained in Test No. 1 by both methods. The pressures at the end of ejection have been given because they probably represent more closely than the initial values the pressures at which complete ejection could take place for a constant-pressure process. Figure 42 shows a graph of propellant weight required versus pressure for this particular test configuration. Figure 43 shows this data reduced to a basis of pounds of propellant per cubic foot of ballast.

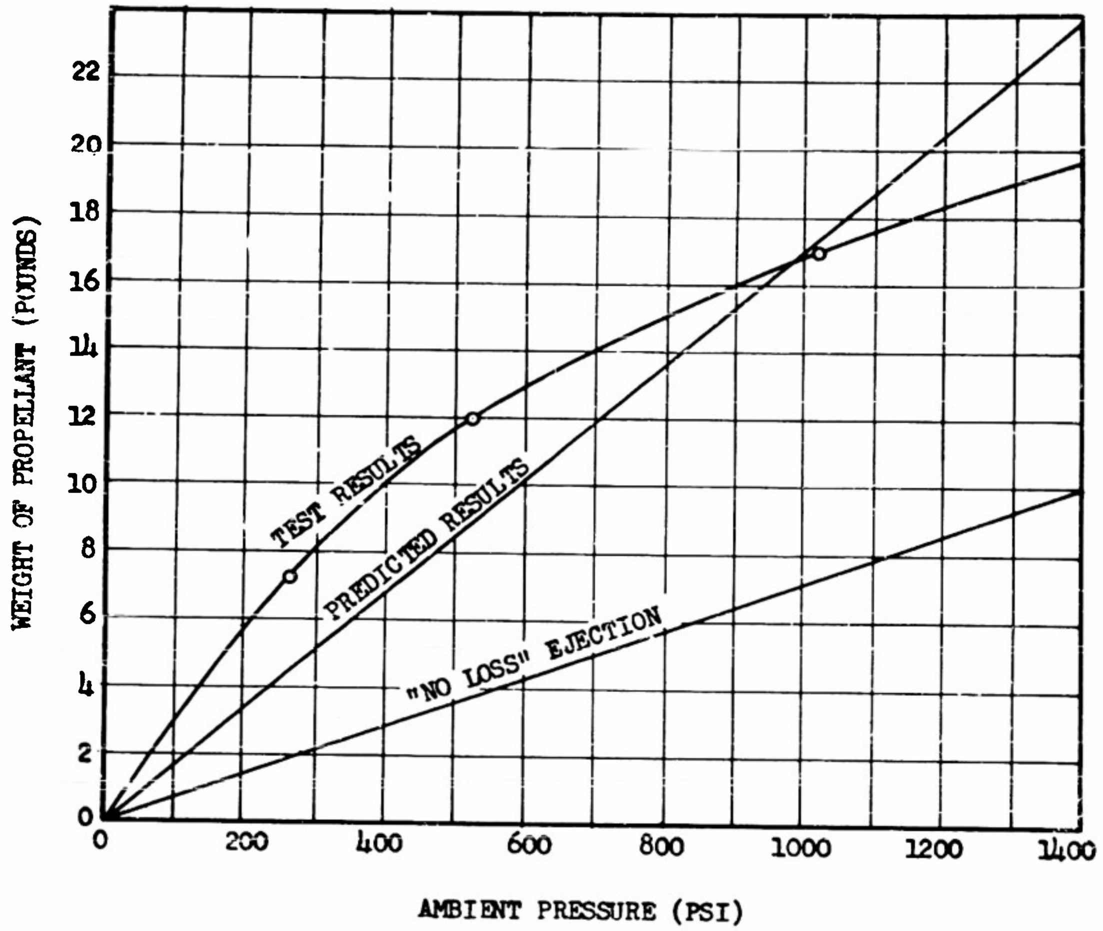


Figure 42. Weight of JPL-128 Propellant Required for Ballast Ejection

It should be noted that the above results apply to a specific system. The number of rocket motors, the number and type of diffusers, the composition of the propellant grain, and any changes in configuration, volume, or ratio of initial to total volume will certainly affect the efficiency of the ejection process.

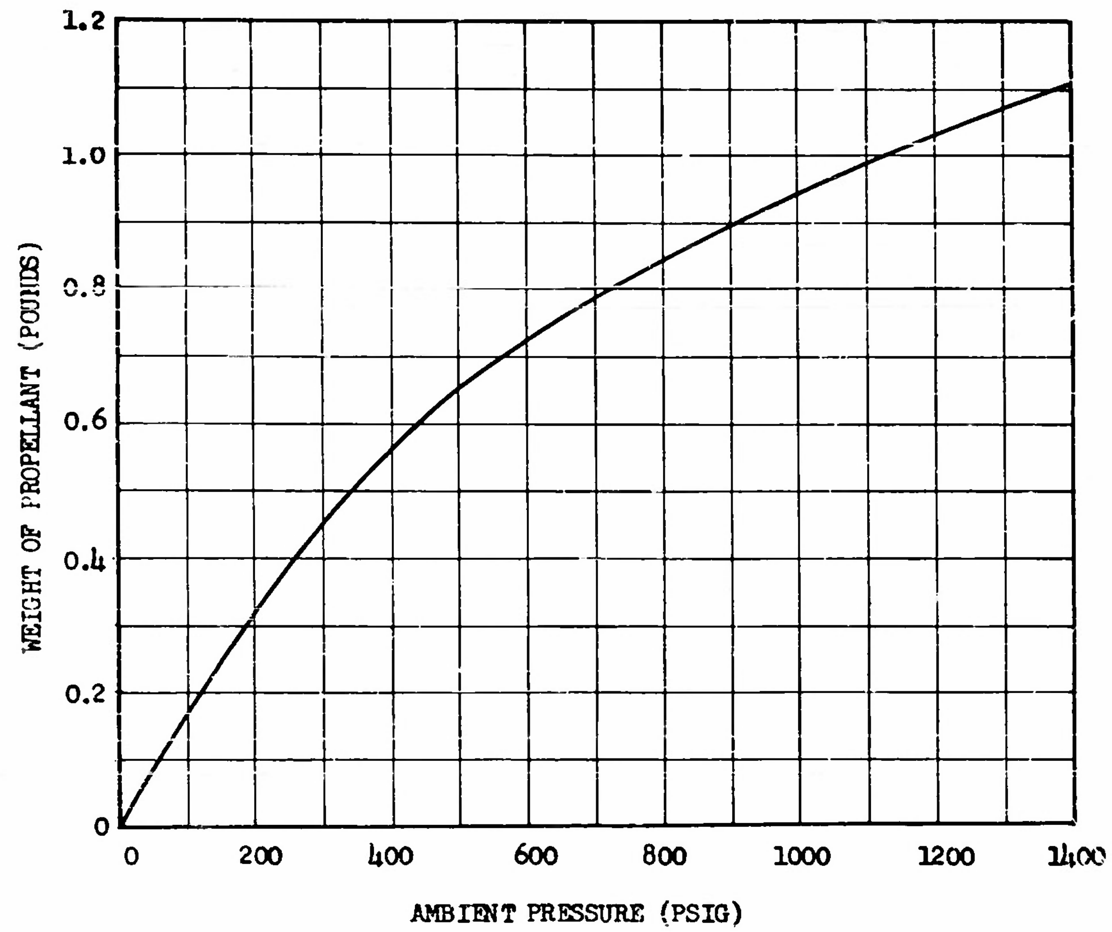


Figure 43. Approximate Weight of JPL-128 Propellant Required per Cubic Foot of Ballast

Ballast Re-entry

The successful operation of the target-seeking mine depends upon the maintenance of full buoyancy (or nearly so) once the ballast has been ejected. The test data indicates the ballast level during the tests, but these results do not apply directly to the mine because the rates of ambient pressure change are not the same for the two cases.

The mine starts its attack vertically, and will have a vertical terminal velocity slightly in excess of 60 feet per second. As the mine maneuvers to intercept a target its vertical component of velocity will be reduced but during the early stages of ascent, which represent the critical period for ballast re-entry, this reduction will not be large. For purposes of computation the figure of 60 feet per second will be used as the ascent rate.

It will be assumed that the gas volume that would have existed in the mine can be determined by an adiabatic expansion from the gas volume in the test cell at the same time. This method does not consider all the possible effects, but should yield results accurate enough to be useful.

Let

t = time from start of ejection

p_m = ambient pressure for mine

p_a = initial ambient pressure (for mine) or pressure at end of ejection (for test cell)

p = tank pressure (as a function of time)

V_m = gas volume in mine

V = gas volume in test cell

Making the assumption that the mine starts rising at full speed when $t = 1.2$

$$p_m = p_a - (0.445)(60)(t - 1.2)$$

The gas temperature is not known, but $\gamma = c_p/c_v = 1.37$ will be used for the buoyant gas.

$$V_m = V\left(\frac{p}{p_m}\right)^{1/\gamma}$$

The computation of V_m is shown in Table 8. There is apparently no ballast re-entry problem for initial pressures up to about 600 psi. For a mine used at an ambient pressure of 1020 psi (corresponding to Test No. 5) the

TABLE 8
BALLAST RE-ENTRY COMPUTATION FOR RISING MINE

Test No.	t (sec)	p (psi)	pm (psi)	V (ft^3)	Vm (ft^3)
1	1.2	265	265	20.6	20.6
1	5	250	147	20.2	29.8
1	10	237	2	19.8	-
1	15	224	-	19.7	-
1	20	212	-	19.8	-
3	1.2	523	523	23.6	23.6
3	5	506	403	21.7	25.6
3	10	499	264	20.3	32.3
3	15	494	125	19.3	52.5
3	20	487	-	18.6	-
5	1.2	1020	1020	23.6	23.6
5	5	986	883	20.8	22.5
5	10	962	727	18.5	22.7
5	15	947	578	17.1	24.5
5	20	933	431	15.9	27.9

computed ballast level and the test data are shown in Figure 44. This data indicates that some re-entry would occur because $\overline{V}_m$ is less than the initial value for about 13 seconds. However, this is a small fraction of the time of flight and should not appreciably affect the trajectory.

Heat Loss Through Insulation

In order to determine the effectiveness of the thermal insulating material, the heat loss through the insulation will be compared with the total

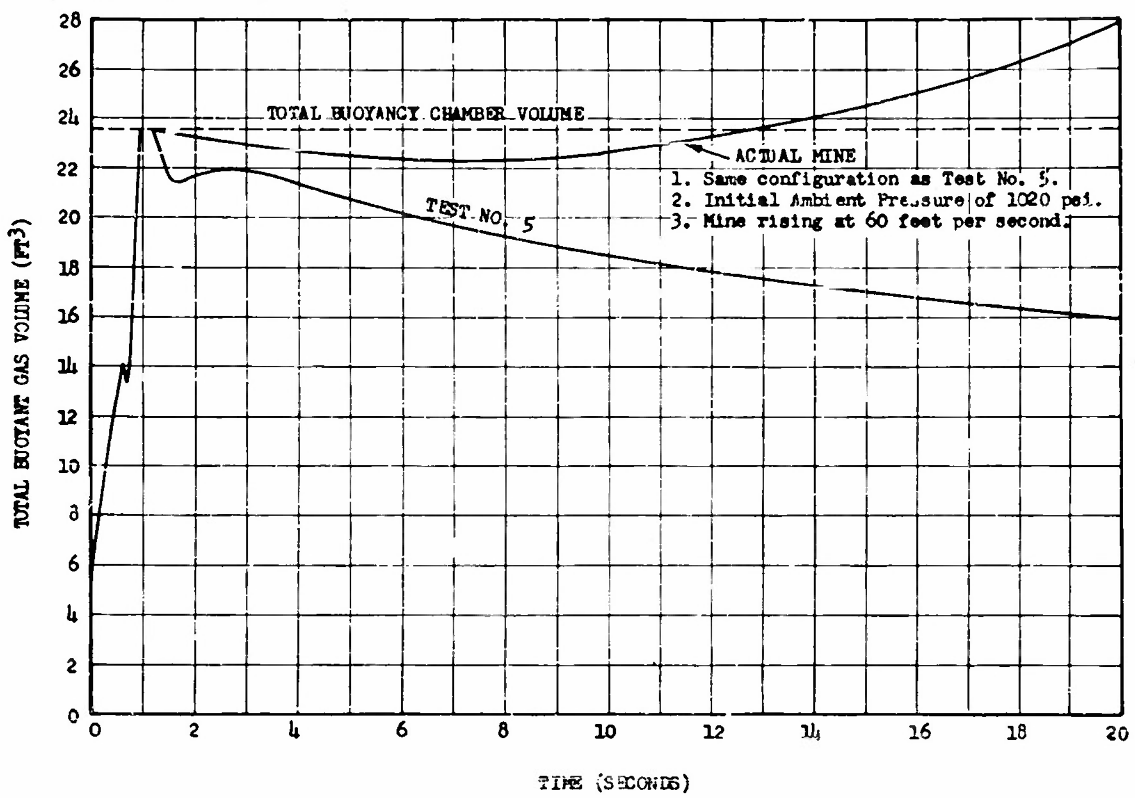


Figure 44. Estimated Ballast Re-entry for Target-Seeking Mine

that could be tolerated without ballast re-entry if the cell were filled with a perfect gas. This approach will yield only an approximate evaluation because the heat flux may well be far from uniform over the surface of the test cell; and the calorimeter block, located at the lower end of the cylindrical portion of the ballast chamber, may not be on the optimum location to measure the average. Heat and soluble components lost to the ballast, and the condensation of water vapor, will account for loss in volume greater than that indicated by loss through the insulation.

If no ballast re-entry is to occur the gas volume must remain constant (or expand). For a perfect gas at constant pressure,

$$q = \frac{C_v}{R} V \frac{dp}{dt}$$

where q = rate of heat flow to gas (Btu/sec)

C_v = molal heat capacity at constant volume (Btu/°F lbm-mol)

R = gas constant = $10.71 \text{ psi ft}^3 \frac{\text{lbm}}{\text{lbm-mol}} \Big/ \text{lbm } ^\circ\text{R}$

V = volume (cubic feet)

p = pressure (psi)

t = time (seconds)

As stated earlier the temperature is not known, and hence C_v cannot be evaluated exactly, but a value of $C_v = 5.4$ is reasonable and will be used.

For a rise rate of 60 feet per second,

$$\frac{dp}{dt} = -(0.445)(60) = -26.7 \text{ psi/sec}$$

The allowable heat loss is then

$$-q = \frac{(5.4)}{10.71}(23.6)(27.6) = 318 \text{ Btu/sec}$$

The heat flux into the calorimeter block was computed from the heat capacity of the block as determined earlier (3.20 Btu/sec) and the temperature rise in the block for a given time interval (Figure 40). The values of heat flux and the total rate of heat loss using an area of 55.7 square feet are shown in Table 9. It can be seen that the heat loss through the insulation appears to be greater than allowable for Test No. 5

TABLE 9
INSULATION HEAT FLUX AND TOTAL RATE OF HEAT LOSS

Test No.	Initial Time (sec)	Time Interval (sec)	Temp. Rise (°F)	Heat Flux (Btu/ft^2 sec)	Rate of Heat Loss (Btu/sec)
1	1.2	3.8	0.1	0.1	5
1	5	5	0.4	0.3	14
1	10	5	1.0	0.6	36
1	15	5	1.4	0.9	50
3	1.2	3.8	0.7	0.6	32
3	5	5	4.4	2.8	157
3	10	5	5.3	3.4	189
3	15	5	5.1	3.3	182
5	1.2	3.8	5.1	4.3	239
5	5	5	11.4	7.3	406
5	10	5	10.6	6.8	378
5	15	5	9.7	6.2	346

From the above considerations as well as those in the section on ballast re-entry, it appears that for ambient pressures above a value which lies somewhere between 600 and 1000 psi the effectiveness of the thermal insulation should be increased to prevent ballast re-entry.

Use of Hydrogen Atmosphere

As discussed earlier, nitrogen was used for all pressurization during the ballast expulsion tests as a safety precaution. However, it is anticipated that the gas used for initial buoyancy in any target-seeking mine will be hydrogen. The question arises as to what effect this change will have.

When the combustion gas mixes with hydrogen, a number of reactions of minor importance will occur, but the only one of any significance is

$$CO_2 + H_2 \longleftrightarrow CO + H_2O$$

With the data at hand it is not possible to solve for the equilibrium composition of the mixture under test conditions. However, since carbon dioxide is present to the extent of only 5.5% in the combustion gas the heat of reaction should not have a large overall effect. Furthermore, the total number of mols, as well as the number of mols likely to be lost to the ballast (carbon dioxide and water vapor) remains unchanged during the reaction.

The one factor that may be of considerable significance is the difference in specific heats of nitrogen and hydrogen. Since that of hydrogen is considerably lower it would be expected that less propellant would be needed because of the higher mixture temperature, but that ballast re-entry would become more of a problem because of the lower allowable rate of heat loss.

IV.

PROCEDURES AND RESULTS

Partial Buoyancy Tests

BASIC TEST AND INSTRUMENTATION PLAN

In the Phase A study (Reference 1) it was determined that a partial buoyancy gas volume of 8 cubic feet would be required during the descent and anchored periods of the mine. Further, it appeared that of the various methods considered for generating the required gas, the reaction of a chemical with sea water to produce hydrogen would be the most convenient. Although calcium hydride is not the most efficient of the chemicals considered, it was chosen because of availability, low cost, and ease of handling.

Since it was desired to maintain a constant gas volume during a period of rising pressure it was decided to use a self-regulating gas generator so designed that when the ballast rose above a fixed level within the ballast chamber the ballast would wet the calcium hydride and generate hydrogen until the ballast had been forced back to the desired level. Although the rate of

descent was not specified in the Phase A study it was felt that about 10 to 15 feet per second would be acceptable, and the larger figure was chosen for the purposes of this test.

Since no large pressure differentials were anticipated, the ballast chamber that had been damaged in ballast expulsion Test No. 2 was straightened with hydraulic pressure for the initial buoyancy tests. The cell and its bulkhead were used as in the ballast expulsion tests except that the water jacket was omitted.

Although several rather complicated reactor designs were considered, it was finally decided that a simple flat basket with wire mesh at top and bottom would be the most satisfactory for the tests. This design would spread the calcium hydride out horizontally with minimum depth, sharply define the internal water level, and provide maximum area for settling out the insoluble calcium hydroxide reaction product.

The general plan for conducting the test was to initially have no gas space in the pressure tank except for nitrogen within the test cell which would extend only a slight distance below the calcium hydride, the remainder of the space being filled with ballast. Then when the test was started and nitrogen was added to the tank, only a small gas volume would be formed at the top of the tank before the ballast contacted the calcium hydride and commenced the reaction. The generation of hydrogen should then prevent further entry of ballast into the test cell and the small volume of gas within the tank could be pressurized from the nitrogen cylinders at the desired rate.

Pressure and ballast level were measured and recorded with the same instrumentation described under the ballast ejection tests.

DESIGN OF TEST EQUIPMENT

Hydrogen Generator

Preliminary tests at atmospheric pressure had indicated that 3/4-inch mesh calcium hydride could be expected to react completely within 60 seconds and 1/4-inch mesh material within 15 seconds when kept submerged in water. On the basis of these tests crushed calcium hydride with 1/4- to 3/4-inch mesh specification was purchased.

For an 8-cubic-foot volume of hydrogen at 1000 psi and 65° F the weight of calcium hydride necessary was calculated to be 30 pounds, which was expected to occupy about one cubic foot.

The calcium hydride basket was made 5-3/4 inches high by 24 inches in diameter with the ends covered with 1/8-inch mesh stainless steel wire screen, the top being removable. Figure 45 shows the basket in place in the ballast chamber, the bottom of the basket being at a level corresponding to a volume of 7.8 cubic feet from the bulkhead.

Instrumentation

The pressure recording system was identical to that used in the ballast ejection tests.

Six spark plug electrodes were used with the ballast level indicating system with the placement changed (as shown in Figure 46) because of the smaller range of ballast levels anticipated.

Safety Precautions

Since no pressure transients were anticipated the safety precautions taken were mostly associated with preventing the generated hydrogen from

Figure 45. Hydrogen Generator Installed in Ballast Chamber

mixing with air. In order to accomplish this, nitrogen was used both as the initial gas in the ballast chamber and for pressurization, and provision was made for venting the resulting gas from the building. A 1450-psi burst diaphragm was also installed.

TEST NO. 1

Starting with the test cell already installed in the tank, the tank was filled with tap water containing 125 pounds of salt until the level inside the chamber was within a few inches of the position where the calcium hydride

basket was to be placed. The basket containing the calcium hydride was then secured in place and the bulkhead put on the cell and bolted down.

The ballast was expelled from the chamber with nitrogen, the tank filled as far as possible with water, the lid put on the tank and locked in place, and the ballast chamber purged of air with nitrogen. Water was added to expel the gas from the top of the tank and to bring the level within the chamber up to the bottom ballast level electrode. The level was then dropped slightly by letting 0.7 cubic foot of water drain from the bottom of the tank.

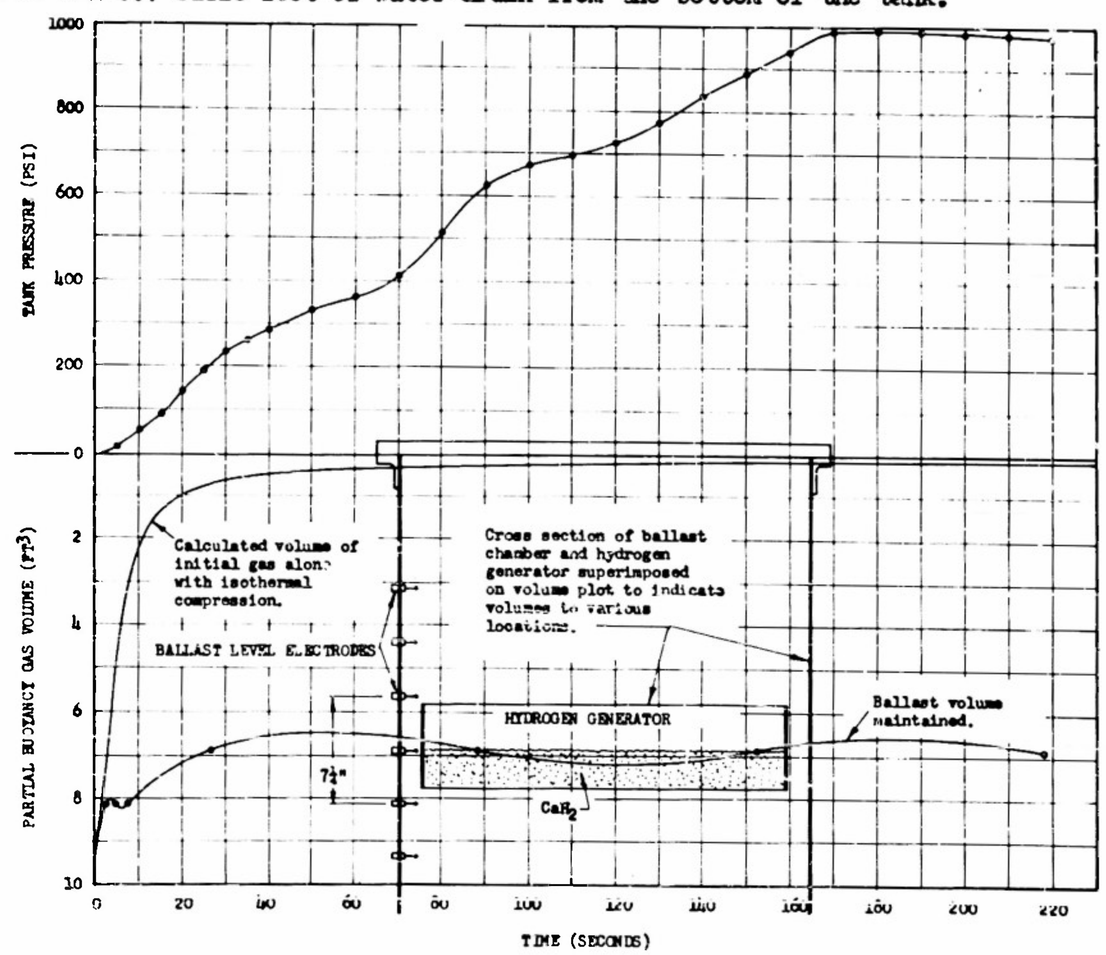


Figure 46. Maintenance of Partial Buoyancy by Means of Hydrogen Generator

The actual test consisted merely of starting the oscillograph and adding nitrogen to the tank under manual control at a rate that would increase the tank pressure by 6 to 7 psi per second (corresponding to a mine descent rate of 15 feet per second). When the pressure reached about 600 psi the burst diaphragm suddenly failed, halting the test and releasing a large quantity of hydrogen into the laboratory. Fortunately, the building was open at each end and the prevailing breeze quickly removed the hazard. The failure was found to have been caused by faulty installation of the burst diaphragm.

TEST NO. 2

After a new burst diaphragm had been properly installed, Test No. 2 was conducted in the same manner as that just described except that only 25 pounds of calcium hydride was used because observation of the first test indicated that the gas temperature was probably higher than had been anticipated. This test was quite satisfactory even though the calcium hydroxide reaction product (of about the consistency of plasterer's lime) had not settled out as expected.

Since the oscillograph record is of considerable length it cannot be satisfactorily reproduced here, but the data that was taken from the record is shown in Figure 46.

TEST RESULTS

As the result of manual control of nitrogen flow to the pressure tank the rate of pressurization was not very constant, but this variation should in no way invalidate the results. It can also be seen from Figure 46 that the ballast level was maintained closer to the top of the calcium hydride than

to the bottom, probably as the result of calcium hydroxide formation at the bottom of the basket which prevented free entry of water into the calcium hydride mass. However, the system was quite effective in maintaining this level as can be seen by comparing the gas volume with that which would have resulted with isothermal compression of the initial gas with no hydrogen generation.

V.

CONCLUSIONS

The ballast displacement data obtained from five test firings is summarized in the propellant weight versus ambient pressure graph of Figure 42. A "no-loss" curve is shown, representing an ideal situation in which no reduction in combustion gas volume takes place, either through heat or mass transfer. It can be seen that the process efficiency increases with pressure and approaches 50% at 1400 psi (520 fathoms). An explanation of this change in process efficiency cannot be made from the available data, but it is suspected that the rates of heat and other losses during the burning period are controlled largely by the temperature at the ballast interface, resulting in higher efficiency as the pressure and gas temperature increase. It follows that the propellant weight required for a given ballast displacement is not a linear function of the depth. However, this does not preclude the use of several identical gas generators to provide the required flexibility in the tactical employment of the mine at various depths.

The data obtained is considered adequate for the design of a prototype mine of the size and configuration proposed in the Phase A study, provided that JPL-128 propellant or nearly equivalent is used in the ballast ejection generators, and that corrections are made for the expected differences in composition and volume of the gas used for initial buoyancy. It is also believed that the data, when reduced to a unit volume basis, is a good first approximation for the design of a prototype mine which is not radically different in size and configuration.

Qualitatively, several particularities were observed that will require specific attention in the final design. Proper baffling of the gas jet from the solid propellant is important from the standpoint of keeping an intact ballast interface and to prevent deterioration of the wall insulation at the higher pressures. A head of gas is necessary to cushion the initial transient pressure generated by ballast inertia and thus keep the differential pressure across the chamber wall at a reasonably low value. Presumably this can be realized from the gas provided for initial buoyancy. The wall insulation appears to play a major role in preventing volume shrinkage after ballast ejection, particularly at the higher pressures, and must be made sufficiently effective to prevent ballast re-entry. During ballast ejection, the greatest loss is apparently to the ballast, and probably not much can be done to improve the situation.

In the generation of hydrogen for initial buoyancy, there appears to be no problem in reaction rate at high pressures, but factors such as the slow reaction of the calcium hydride in a moist atmosphere may require a more

complex generator design for a long standby life. However, the tests have provided sufficient evidence to indicate that the generation of partial buoyancy with a water-reactant chemical such as calcium hydride, and of the final buoyancy with a solid propellant such as JPL-128 are practicable approaches to these requirements and present no insurmountably difficult design problems.

REFERENCES

1. HAC Report No. 09-168-D, Research on the Design of a Target-Seeking Mine, 30 November 1952, SECRET.

2. Carslaw and Jaeger, Conduction of Heat in Solids, Oxford University Press, 1947; page 104.

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